**ALMA MATER STUDIORUM - UNIVERSITÀ DI BOLOGNA**

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# *Ventilated façades and thermal coatings compared: environmental product declaration and energy certification in a study case*

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Francesca Battistini

# INDEX

# INTRODUCTION

Since the construction sector is responsible for a large part of environmental pollution all around the world, the current situation is characterized by the need of rethinking the sustainability of existing buildings. My research meets the essence of combining studies of construction technologies from two different angles: the environmental impact of construction materials on one side and the energy consumption for the building management on the other side. This thesis is divided into four chapters. Chapter one discusses in more detail about the framework of the environmental problem in the building sector. Some alternative methods for sustainable redevelopment of buildings are described, such as the use of *phase change materials* (PCMs) and *double skin façades* (DSFs). Following the trend towards a more sustainable use of energy resources suggested by the European Union in *2020-2030-2050 Energy Strategies*, both the *life cycle assessment* (LCA) method and the *environmental product declaration* (EPD) eco-label are outlined. LCA must be performed in adherence to ISO 14040 and 14044, while EPD is standardized by ISO 14025. Chapters two and three compare the building renovations from both the environmental and energy performances point of views. The environmental analyse is performed by using the *EPD 2008* method (*SimaPro 7* software), which provides results allocated in six impact categories: global warming, ozone layer depletion, photochemical oxidation, acidification, eutrophication and non-renewable resources depletion. The quantities of materials used for the restructuring are calculated considering a complex real case: the requalification of the hospital of *San Benedetto Del Tronto* using different structures (thermal coatings or ventilated façades with aluminum or ceramic cladding) and different insulating materials (polyurethane, rock wool or glass wool). Regarding the calculations of energy needs, a simpler and rapid alternative to the hospital building complexity is developed. The simplified but realistic study case is a condominium of four apartments. The amount of $CO_2$ production connected to the energy use to manage the heating of the building is calculated using UNI 11300 and *Edilclima* software. Comparison between the energy consumption of the building with different kind of walls (thermal coatings and ventilated façades) are made. Chapter 4 draws conclusions from chapter two and three because it defines the best requalification option from the environmental point of view, considering both the environmental impact of the material constituting the external walls and the $CO_2$ production for the managing of the heating system and the production of domestic hot water.

# 1. FRAMEWORK OF THE ENVIRONMENTAL PROBLEM AND SUSTAINABILITY

## 1.1 ENERGY STRATEGIES OF EUROPEAN UNION

As commercial and residential buildings in Europe consume approximately 40% of primary energy and are responsible for 24% of greenhouse emissions [1],[2], improving the energy performance of buildings is a main opportunity to satisfy the energy challenge set by the *European Union* (EU) for 2020, 2030 and 2050.

**2020 Energy Strategy of European Union** [3]

- Reduction of greenhouse gas emissions by at least 20%.
- Increase in the share of renewable energy to at least 20% of consumption.
- Achieving the 20% or more in energy saving.
- Fulfilment the 10% of share of renewable energy in transport sector by each member of EU.

The aims of these targets are combatting climate change and air pollution, decreasing the dependence of EU on foreign fossil fuels and keeping energy affordable for consumers and businesses. In the interest of meeting the goals regarding the building sector, the 2020 Energy Strategy set out investment into efficient buildings, energy labelling schemes, renovation of public buildings and eco-design requirements for energy intensive products as priorities.

**2030 Energy Strategy of European Union** [4] (it includes objectives from 2020 to 2030)

- A 40% reduction in greenhouse gas emissions compared to 1990 levels.
- At least a 32% share of renewable energy consumption, with an upward revision clause for 2023.
- Indicative target for a rising in energy efficiency at EU level of at least 32.5%, following on from the existing 20% target for 2020.

- Completion of the internal energy market by achieving the existing electricity interconnection target of 10% by 2020, with a view to reaching 15% by 2030.

2030 Energy Strategy represents a moment of transition to the 2050 Energy Strategy and policies for 2030 focus on create a new governance system based on national plans for competitive, secure, and sustainable energy.

**2050 Energy Strategy of European Union** [5] describes the Energy Roadmap 2050: it displays the transition of the energy system in ways that would be compatible with the 2050 greenhouse gas reduction target, while also increasing competitiveness and security of supply.

- Reduction of greenhouse gas emissions by 80-95%, when compared to 1990 levels, by 2050.

Routes set out by Energy Roadmap 2050

- Energy efficiency
- Renewable energy
- Nuclear Energy
- Carbon capture and storage

PCMs are validated as an effective way to improve building's energy management. Such materials can store a large amount of energy due to a transition of phase that is most frequently the solid/liquid one. This can enhance the building thermal mass and thus leads to energy efficiency and energy savings meeting European targets. As the low replacement rate of existing buildings with new ones, the energy retrofitting of the existing building stock is of outmost importance to reach the EU objectives and promote energy efficiency and environmental sustainability. To move away from the linear economic model of 'take, make, and waste' and towards the circular economy of resource efficiency, EU created a voluntary framework to improve the sustainability of buildings called Level(s). Level(s) is a tool for designing and constructing sustainable buildings, so they use less energy and materials, and are healthier and more comfortable spaces for occupants. The European Commission opened a two-year testing phase for Level(s) indicators in spring 2018.

## 1.2 LIFE CYCLE ASSESSMENT

*Life Cycle Assessment* (LCA) is an analytical tool used to quantify and interpret the environmental flows to and from the environment, over the life cycle of a product or process; for this reason, it is also called “cradle-to-grave” analysis. It must be performed in adherence to the International Organization for Standardization (ISO) 14040 and 14044 series of standards. Overall, LCA is a technique for assessing the potential environmental aspects associated with a product (or service), by [6]:

1. Defining goals and scoping: identifying the LCA's purpose, the expected products of the study and determining the boundaries (what is and is not included in the analysis). The scope depends on the topic under investigation, as well as the planned use of the generated results. The goal and scope definition phase also requires the definition of the system boundaries, the functional unit, the impact categories to be investigated, as well as the relevant scenario to be developed.

2. Specifying Life-cycle inventory: compiling an inventory of inputs and outputs, quantifying both the energy and raw material inputs and environmental releases associated with each stage of production. This phase involves the collection of all necessary for the calculation of the environmental impact data, which can be retrieved from relevant studies, industrial, governmental and public databases, scientific publications and from established local and global databases of the employed LCA tool.

3. Estimating impact analysis: evaluating the potential environmental impacts (influence on human health included) associated with inputs and outputs quantified in the inventory and mentioned in the previous step. The object of this phase is to provide additional information for the definition and understanding of the environmental significance of the inputs and outputs in the study. The impact assessment phase converts the inventory emission data into damage indicators of potential environmental impacts; it also involves several sub-processes like classification, characterization, grouping and weighting.

4. Outlining improvement analysis: interpreting the results in relation to the objectives of the study and evaluating opportunities to reduce energy, material inputs or environmental impacts at each stage of the product lifecycle. In this phase the results of the analysis are summarized and discussed as a basis of conclusions, recommendations and decision-making in conformity with the initial goal and scope definition phase.

Calculations on *Carbon footprint of products* (CFPs) are included in the LCA because it assesses the amount of *greenhouse gasses* (GHG) emitted and removed from cradle to grave.

## 1.3 ENVIRONMENTAL PRODUCT DECLARATION

Generally, the use of thermal insulation materials in buildings has both economic and ecological consequences because it reduces energy demand for heat in the use phase of the building. As a result, due to the reduced energy consumption, both the environmental load and the cost of heating decrease. However, it is necessary to be aware that the production and the installation of the thermal insulation itself result in certain economic costs which also increase the environmental load. LCA methodologies were in the first instance developed to create decision support tools for distinguishing between products, product systems, or services on environmental grounds. During the development of the methodology, several related applications emerged, including its use as basis to communicate the overall environmental performance of the products to stakeholders. An *Environmental Product Declaration* (EPD) is a label standardized by the *International Standards Organization* (ISO 14025) and LCA-based tool to communicate the environmental performance of a product. The purpose of an EPD in the construction sector is to provide the basis for assessing buildings which cause less stress to the environment; it also provides information on emissions to indoor air, soil and water during the use stage of the building. Based on EN 15804, there are three types of EPD according to the LCA information they cover:

- "*cradle to gate*" EPD covers raw material supply, transport, manufacturing and associated processes.
- "*cradle to gate with options*" EPD covers product stage and selected further life cycle stages.
- "*cradle to grave*" EPD covers product stage, installation into the building, use and maintenance, replacement, demolition, waste processing for re-use, recovery, recycling and disposal.

As already mentioned, an EPD is a certified *Environmental Product Declaration* (ISO type III declaration), which reports environmental data over the life cycle of products in accordance with the *International Standard* ISO 14025. It allows to quantify environmental information on the life cycle of a product and to enable comparisons between products fulfilling the same function (Bovea et al.) [7]. In particular, the European Standard EN 15804 defines EPD related to the construction sector. There are six default impact categories to use in an EPD: global warming, ozone layer depletion, photochemical oxidation, acidification, eutrophication and non-renewable depletion.

- *Global Warming Potential* (GWP100) [kg $CO_2$ eq.] expresses the contribution to the greenhouse effect of a greenhouse gas up to a specific time horizon, relative to *carbon dioxide* ($CO_2$). Therefore, the $GWP_{CO2}$ is equal to 1. It gives a measure of how much of a given mass of a chemical substance contributes to global warming over a given period. The formula is as follows:

  $$GWP(x) = \frac{\int_0^{TH} a_x \cdot [x(t)]\, dt}{\int_0^{TH} a_r \cdot [r(t)]\, dt}$$

  where *TH* stands for "time horizon", $a_x$ is the "radiative efficiency" due to a unit increase in atmospheric abundance of the substance, *x(t)* is the time-dependent decay in abundance of the substance following an instantaneous release of it at t=0; in denominator there are the same quantities relative to $CO_2$. It is calculated for each different *greenhouse gas* (GHG) which are: $CO_2$, $N_2O$, $CH_4$ and *volatile organic compounds* (VOCs). As already said, GWP is expressed as $CO_2$ equivalent.
- *Ozone Depletion Potential* (ODP) [kg CFC-11 eq.] indicates the decomposition of *ozone* ($O_3$) molecules, present in the upper atmosphere and working as a shield against the UVB emitted by the sun, due to the release of pollutants contained in chemical products. The reference is *trichlorofluoromethane* (CFC-11); therefore $ODP_{CFC}$-11 is equal to 1.
- *Photochemical Oxidation Potential* [kg $C_2H_4$ eq.] refers to the photochemical smog caused by the degradation of *volatile organic compounds* (VOCs) and *nitrogen* (N) and is expressed in kg of *ethylene* ($C_2H_4$).
- *Acidification Potential* (AP) of land and water [kg $SO_2$ eq.] is a consequence of acids being emitted to the atmosphere and subsequently deposited in surface soils

and waters; AP classification factors are mostly based on the contributions of $SO_2$, $NO_x$, HCl, $NH_3$ and HF and expressed as $SO_2$ equivalent.

- *Eutrophication Potential* (EP) [kg $PO_4^{3-}$ eq.] indicates the pollution state of aquatic ecosystems in which the over-fertilization of water and soil has turned into an increased growth of biomass; it is calculated in kg based on a weighted sum of the emission of nitrogen and phosphorus derivatives such as $N_2$, $NO_x$, $NH_4^+$, $PO_4^{3-}$, P and chemical oxygen demand. The classification factors for EP are expressed as *phosphate equivalents* ($PO_4^{3-}$).
- *Non-Renewable Depletion Potential* or *Abiotic Depletion* [kg Sb eq.] is obtained for fossil fuels, metals and minerals by dividing the quantity of resource used by the estimated total world reserves of that resource. It is expressed as *antimony* (Sb) equivalent.

## 1.4 DOUBLE SKIN FAÇADES

Recently, the interest in double skin façades has increased because of esthetic reasons and for its use as passive system to save energy. The drivers behind the decision to adopt double skin façades technologies, in both new and existing buildings, range from aesthetic reasons to more technical ones like providing thermal comfort through passive cooling/heating, energy saving and reduction of *greenhouse gas* (GHG) emissions. *Double skin façade* (DSF) is a hybrid system of building consisting of an external glazed skin and the actual building façade, which represents the inner skin. The two layers are separated by an air cavity which has fixed or controllable inlets and outlets through incorporate vents; the ventilation of the cavity can be natural, fan supported or mechanical. The intermediate space may or may not incorporate fixed or controllable shading devices (Pomponi et al) [8].

Key DSFs parameters are (Figure 1) [8]:

- spatial configuration (*box windows* (BW), *corridor* (C), *shaft box* (SB) and *multi-storey* (MS)),
- cavity width (a *narrow cavity*, width up to 40 cm, may significantly influence air flow and air velocity, while a *wide cavity*, width more of 40 cm, often implies a higher amount of construction materials which increase the embodied energy of DSF),
- ventilation (natural, fan supported, mechanical),
- airflow (*supply air* (SA), *exhaust air* (EA), *air buffer* (AB), *external air curtain* (EAC), *internal air curtain* (IAC)).

Building’s parameters are:

- orientation,
- climatic area (Köppen climate classification).

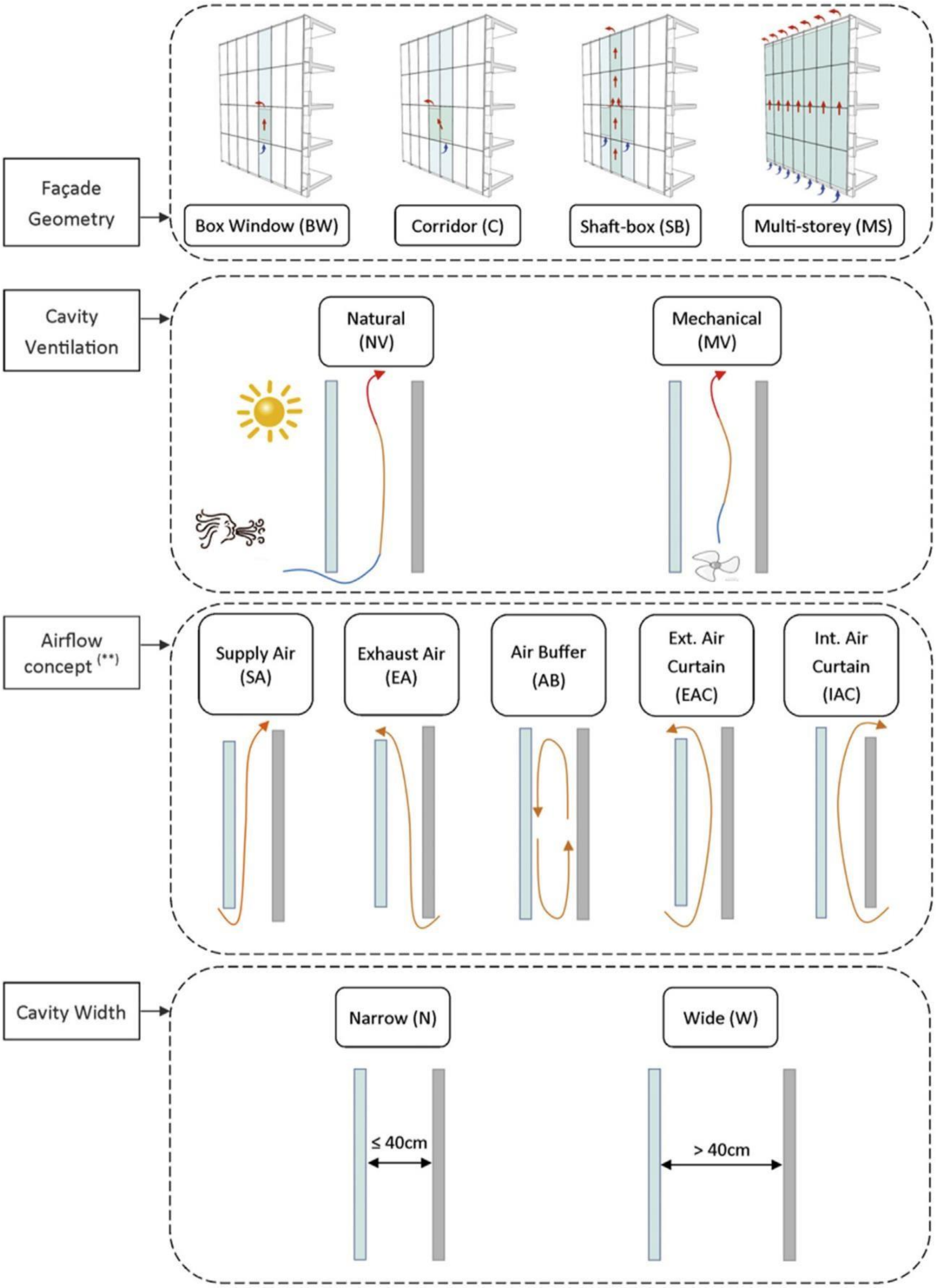



**Figure 1.** Classification of DSFs based on key parameters. [8]

The natural ventilation in the cavity is driven by two forces related to:

- Pressure difference caused directly by wind action: when wind hits a building, the windward side is characterized by a positive pressure which pushes the air into or against the building, the leeward side has a negative pressure which results in a suction of the air out or away from the building.
- Pressure difference caused by thermal buoyancy: it happens when the air density changes due to a temperature change; more specifically, hot air rises and cold air sinks.

A specific DSF is a unique combination of several factors, like the portioning of the cavity with its division and obstruction, the solar radiation and the way it is influenced by shading devices and their position within the cavity, the convection regimes and airflow resistance, the frictional resistance of the materials of the inner and the outer skins and the obstructions in the cavity and their correspond heat transfer coefficients, the cavity openings and vertical temperature gradient; hence the difficulty in achieving consistent and agreed figures on DSF energy performance.

### 1.4.1 EMBODIED ENERGY OF DSFs

Embodied energy is the energy associated with the manufacturing of a product or services in a *cradle to grave* approach. It includes energy used for extracting and processing of raw materials, manufacturing of construction materials, transportation, distribution, assembly and construction. Pomponi et al. highlight that there are only few attempts addressing embodied energy figures and life cycle impacts in a holistic way [8]: the papers of Wadel et al. [9] and Gracia et al. [10] are two examples. The former studied the application of the environmental strategies defined in project FB720 for designing a facade leading to a considerable reduction in environmental impacts throughout the life cycle [9]. The latter, Gracia et al. [10], evaluated the *life cycle assessment* (LCA) of a DSF with a *phase change material* (PCM) in its air chamber, using the Eco-Indicator 99 methodology. Considering a building lifetime of 50 years, they demonstrated that the use of this ventilated façade reduces 7.5% the overall environmental impact. The environmental payback of the system is 31 years, but this period decreases up to 6 replacing the structure with wood profiles [10].

### 1.4.2 OPERATIONAL ENERGY OF DSFs

Operational energy is the energy required during the entire service life of a structure such as lighting, heating, cooling, and ventilating systems, running the equipment and appliances. Heating, cooling, lightening and ventilation are normally influenced by a building façade performance. In the interest of understanding the maximum energy saving potential of the DSF, the results are presented for the “best” case scenario.

#### Heating

The improvement in building sector have high potential in energy demand reduction and in energy savings. The use of the double skin façades has become more and more popular in the building sector and the most widely mentioned supporting arguments is the reduction of heating loads. The mechanism consists of the solar energy passing through the glass façade and transforming into heat. The heat warms up the air in the cavity and creates convectional airflows patterns (air buffer in Figure 1): this process reduces heat losses through the inner skin of the building [8]. All the heat transfer mechanisms and fluid dynamic phenomena are shown in Figure 2. If the quality of the air is satisfactory and an internal air curtain is present, the warmer air in the cavity can be supplied in indoor spaces (supply air and internal air curtain visible in Figure 1).

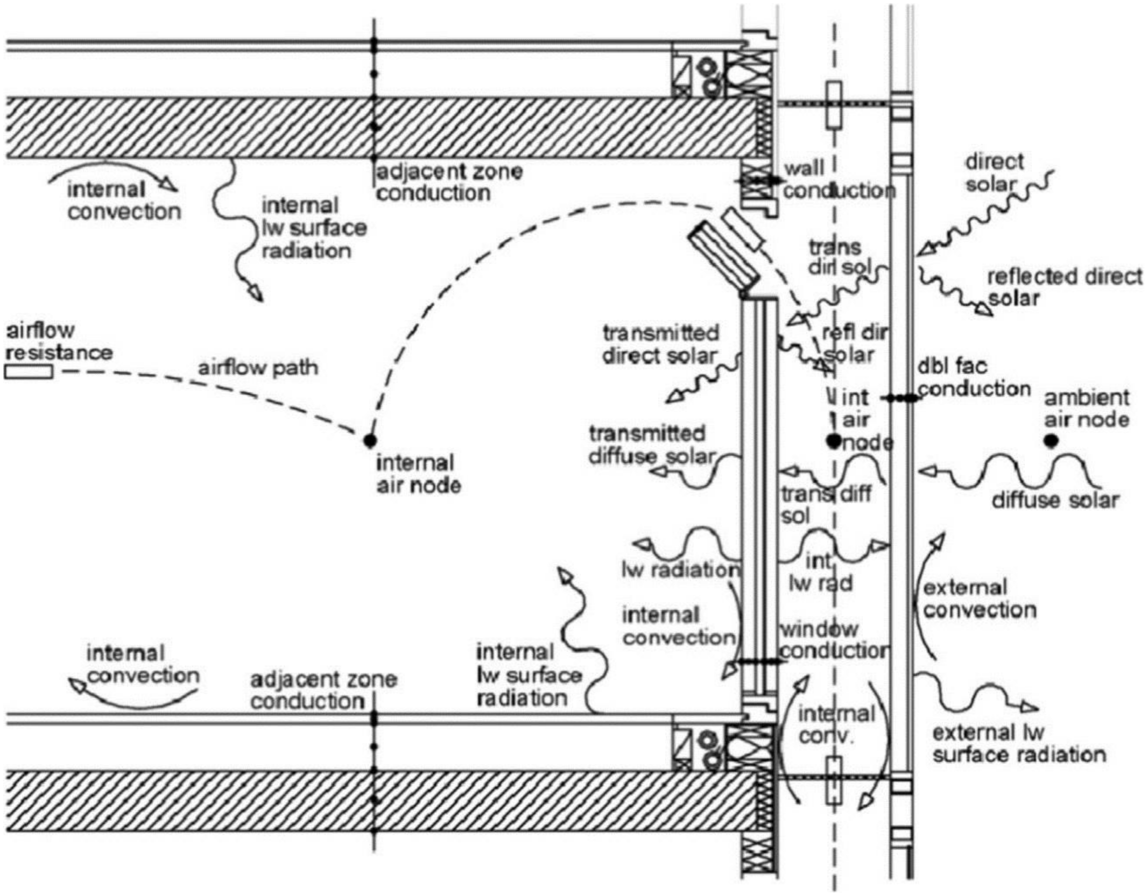



**Figure 2.** Heat transfer mechanisms and fluid dynamic phenomena in DSF [8].

In 2009, Baldinelli compared a DSF to a fully glazed single skin façade in Italy and observed a 65% reduction in heating loads [11]. Similar results have been achieved in the UK, when comparing a DSF to an advanced single skin [12].

## Cooling

Cooling savings correspond to different working principles: the supply of fresh air (supply air in Figure 1), the extraction of the heat from the occupied spaces through the stack effect (exhaust air in Figure 1) and the cooling of the inner skin (external air curtain in Figure 1). All these mechanisms are particularly useful during the night. There is agreed and well-argued concern about overheating during daylight in summer, contributing to indoor discomfort [8].

**Ventilation**

supply fresh and good quality air into the occupied spaces through the DSF, paying attention to design, inlet openings, inlet temperatures and other key parameters [8].

In order to properly understand the true environmental benefit, studies about the *life cycle assessment* (LCA) of DSFs are urgently needed: having an overall holistic performance of a DSF is only possible associating the operational energy savings to the related embodied energy figures. Recently, there has been a growing tendency to apply DSF in refurbishment, combining the operational energy savings with the reduction of environmental impacts related to demolition and reconstruction.

# 2. ENVIRONMENTAL PRODUCT DECLARATION OF BUILDING TECHNOLOGIES

The aim of the thesis is to take into consideration the environmental impacts of different construction methods to redevelop the envelope of the building under study.

In this project, environmental impact results are obtained by using:

- Software: *SimaPro 7*
- Database: *Ecoinvent* system and unit processes
- Method: *EPD (2008)*

The environmental profile is divided into six impact categories as follows: global warming, ozone layer depletion, photochemical oxidation, acidification, eutrophication and non-renewable depletion.

## 2.1 CASE OF STUDY: HOSPITAL OF SAN BENEDETTO DEL TRONTO

The “*Madonna del Soccorso*” hospital located in San Benedetto Del Tronto represents the case of study of this thesis. The building’s façades taken into consideration are D1, D2, D3, D4, D5, D6 and D7 as shown in Figures 3 and 4.

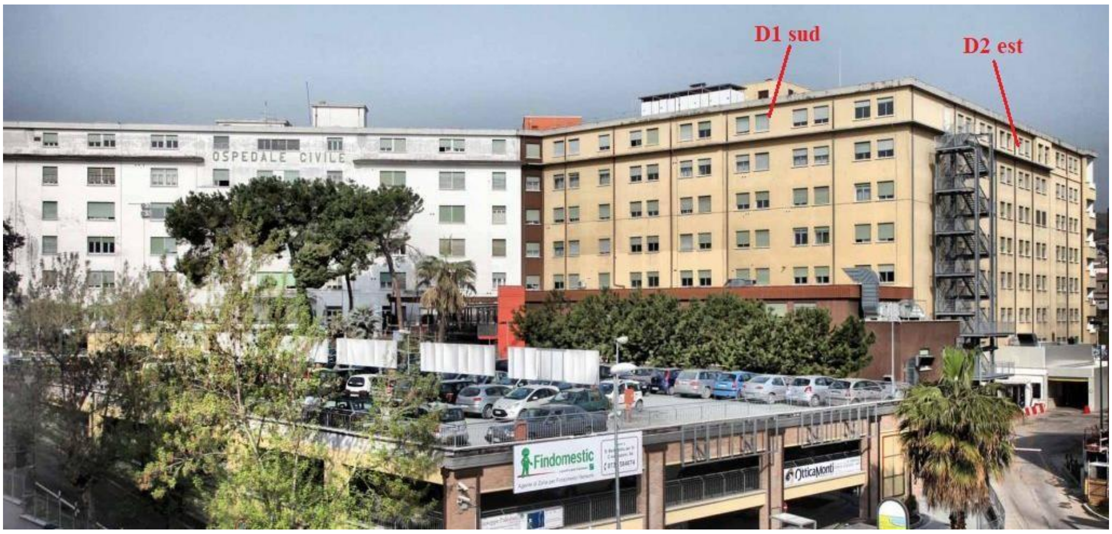



**Figure 3.** Façades D1 and D2 of the hospital of San Benedetto del Tronto. [13]

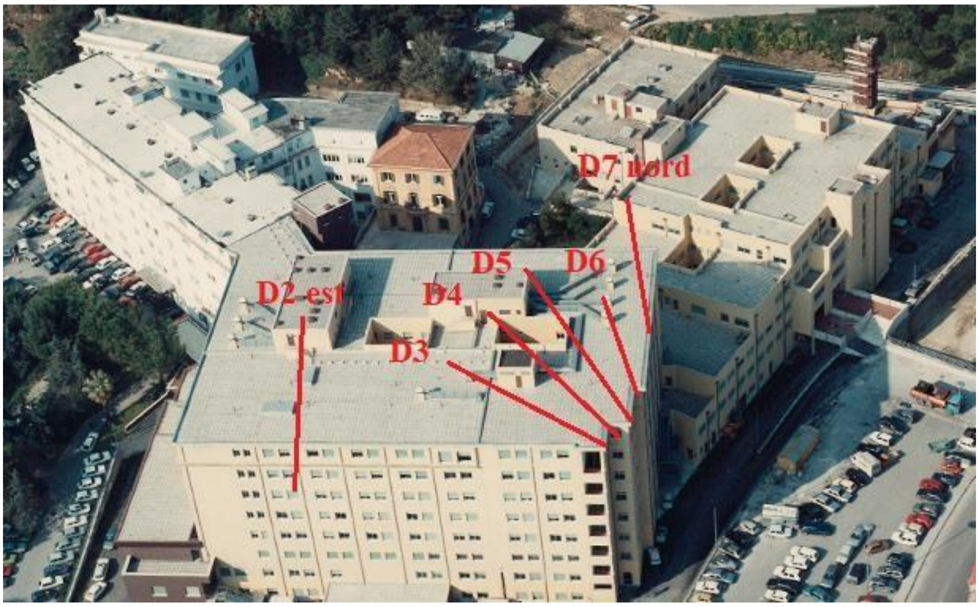



**Figure 4.** Façades D2, D3, D4, D5, D6 and D7 of the hospital of San Benedetto del Tronto. [14]

Façades' surfaces excluding windows and other parts not subjected to future redevelopment (Table 1):

| | façade | windows | effective façade |
|---|---|---|---|
| area | [m2] | [m2] | [m2] |
| D1 | 822,19 | 179,11 | 643,08 |
| D2 | 1038,79 | 215,53 | 823,26 |
| D3 | 105,44 | 0,00 | 105,44 |
| D4 | 60,42 | 14,93 | 45,49 |
| D5 | 154,15 | 29,85 | 124,30 |
| D6 | 31,06 | 0,00 | 31,06 |
| D7 | 626,01 | 114,97 | 511,04 |
| total | 2838,05 | 554,38 | 2283,67 |

**Table 1.** Façades' surfaces.

The purpose of this research is to calculate the environmental impact of this building in seven different redevelopment scenarios, regarding two different structures (thermal coating and ventilated façade) and three insulating materials (polyurethane, rock wool and glass wool):

- Case 1-thermal coating-polyurethane (insulation)
- Case 1-ventilated façade-polyurethane (insulation)
- Case 2-thermal coating-rock wool (insulation)
- Case 2-thermal coating-glass wool (insulation)
- Case 2-ventilated façade-rock wool (insulation)
- Case 2-ventilated façade-glass wool (insulation)
- Case 3-ventilated façade-porcelain tiles (cladding)

### 2.1.1 CASE 1-THERMAL COATING-POLYURETHANE (insulation)

In this case, the facades are covered with a polyurethane thermal coat; specifically, all external surfaces are clad on site using *TermoK8 Slim* (*Ivas*) as shown in Figure 5.

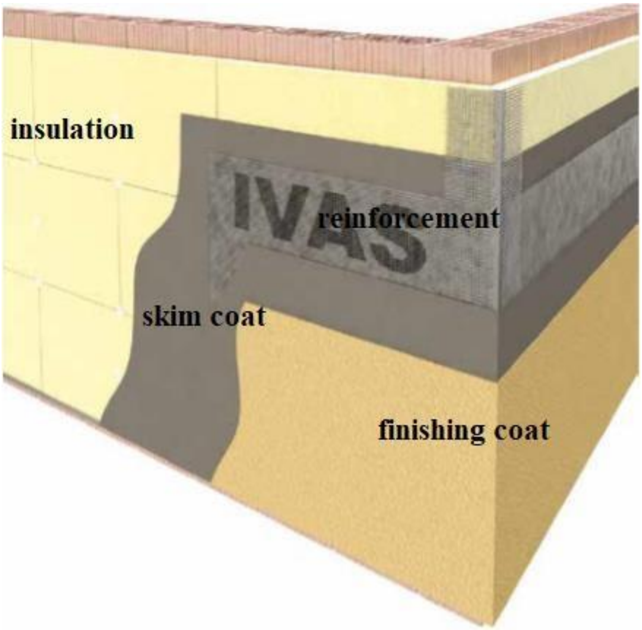



**Figure 5.** *TermoK8 Slim* (*Ivas*). [15]

The following tables contain the quantities of materials necessary for the thermal coating of the façades and the windows' outline (Tables 2 and 3).

| | | | | | D1 | D2 | D3 | D4 | D5 | D6 | D7 | total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | [m2] | [m2] | [m2] | [m2] | [m2] | [m2] | [m2] | [m2] |
| | | | | | 643,08 | 823,26 | 105,44 | 45,49 | 124,30 | 31,06 | 511,04 | 2283,67 |
| element | material | | | [kg/m2] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] |
| Klebocem adhesive | cement | | | 4,50 | 2893,87 | 3704,68 | 474,50 | 204,71 | 559,34 | 139,78 | 2299,67 | 10276,54 |
| | | [kg/m3] | thickness [m] | | | | | | | | | |
| Insulation Stiferite | polyurethane | 35 | 0,089 | 3,12 | 2003,20 | 2564,46 | 328,46 | 141,70 | 387,19 | 96,76 | 1591,88 | 7113,65 |
| | | [kg/el] | [el/m2] | | | | | | | | | |
| EJOT H3 wall anchor | PVC | 0,01337 | 6 | 0,08 | 51,59 | 66,04 | 8,46 | 3,65 | 9,97 | 2,49 | 41,00 | 183,20 |
| Klebocem skim coat | cement | | | 4,50 | 2893,87 | 3704,68 | 474,50 | 204,71 | 559,34 | 139,78 | 2299,67 | 10276,54 |
| | | [kg/m2] | [el/m2] | | | | | | | | | |
| Armatex C1 mesh | glass fiber | 0,15 | 1,1 | 0,17 | 106,11 | 135,84 | 17,40 | 7,51 | 20,51 | 5,13 | 84,32 | 376,81 |
| RivatonePlus finish coat | acrylic resin | | | 3,00 | 1929,25 | 2469,78 | 316,33 | 136,47 | 372,89 | 93,19 | 1533,11 | 6851,02 |

**Table 2.** Façades' thermal coating.

| | | | | | | D1 | D2 | D2 | D2 | D3 | D4 | D5 | D6 | D7 | D7 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | window height | [m] | 1,55 | 1,55 | 2,19 | 2,33 | 0,00 | 1,55 | 1,55 | 0,00 | 1,55 | 1,62 | |
| | | | | window base | [m] | 1,61 | 1,61 | 1,35 | 1,84 | 0,00 | 1,61 | 1,61 | 0,00 | 1,61 | 0,80 | |
| | | | | window depth | [m] | 0,30 | 0,30 | 0,30 | 0,30 | 0,00 | 0,30 | 0,30 | 0,00 | 0,30 | 0,30 | |
| | | | | window outline surface | [m2] | 1,89 | 1,89 | 2,12 | 2,50 | 0,00 | 1,89 | 1,89 | 0,00 | 1,89 | 1,45 | |
| | | | | # windows | | 72,00 | 82,00 | 1,00 | 2,00 | 0,00 | 6,00 | 12,00 | 0,00 | 41,00 | 10,00 | |
| | | | | total contour surface | [m2] | 136,30 | 155,23 | 2,12 | 5,01 | 0,00 | 11,36 | 22,72 | 0,00 | 77,61 | 14,52 | |
| element | material | | | [kg/m2] | | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] |
| Klebocem adhesive | cement | | | 5 | | 681,48 | 776,13 | 10,62 | 25,04 | 0,00 | 56,79 | 113,58 | 0,00 | 388,07 | 72,60 | 1736,25 |
| | | [kg/m3] | thickness [m] | | | | | | | | | | | | | |
| Insulation Stiferite | polyurethane | 35 | 0,03 | 1,05 | | 143,11 | 162,99 | 2,23 | 5,26 | 0,00 | 11,93 | 23,85 | 0,00 | 81,49 | 15,25 | 196,37 |
| | | [kg/el] | [el/m2] | | | | | | | | | | | | | |
| EJOT H3 wall anchor | PVC | 0,01337 | 6 | 0,08022 | | 10,93 | 12,45 | 0,17 | 0,40 | 0,00 | 0,91 | 1,82 | 0,00 | 6,23 | 1,16 | 15,00 |
| Klebocem skim coat | cement | | | 5 | | 681,48 | 776,13 | 10,62 | 25,04 | 0,00 | 56,79 | 113,58 | 0,00 | 388,07 | 72,60 | 935,07 |
| | | [kg/m2] | [el/m2] | | | | | | | | | | | | | |
| Armatex C1 mesh | glass fiber | 0,15 | 1,1 | 0,165 | | 22,49 | 25,61 | 0,35 | 0,83 | 0,00 | 1,87 | 3,75 | 0,00 | 12,81 | 2,40 | 30,86 |
| RivatonePlus finish coat | acrylic resin | | | 2,2 | | 299,85 | 341,50 | 4,67 | 11,02 | 0,00 | 24,99 | 49,98 | 0,00 | 170,75 | 31,94 | 411,43 |

**Table 3.** Thermal coating for windows' outline

The total quantities of each material are summarized in Table 4 and graphed in Figure 6.

| | material | total |
|---|---|---|
| | | [kg] |
| Klebocem | cement | 23224,39 |
| Insulation Stiferite | polyurethane | 7310,01 |
| EJOT H3 wall anchor | PVC | 198,20 |
| Armatex C1 mesh | glass fiber | 407,66 |
| RivatonePlus finish coat | acrylic resin | 7262,46 |

**Table 4.** Total quantities of each material for case1-thermal coating-polyurethane (insulation).

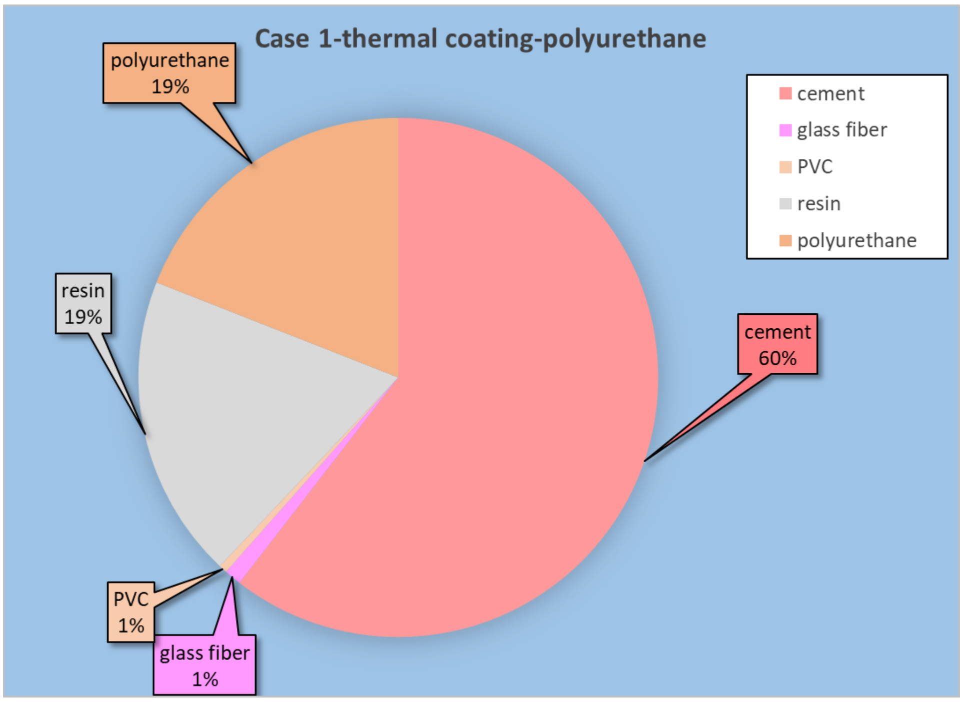



**Figure 6.** Pie chart of the materials used in case 1-themal coating-polyurethane (insulation).

### 2.1.2 CASE 1-VENTILATED FAÇADE-POLYURETHANE (insulation)

In this case, the upgrading of the building consists of ventilated façade wall cladding using polyurethane as insulation and sheets of aluminium alloy as cladding. The figures below (Figures 7 and 8) display the *Alucovering* (*Aliva*) ventilated façade system and his construction elements.

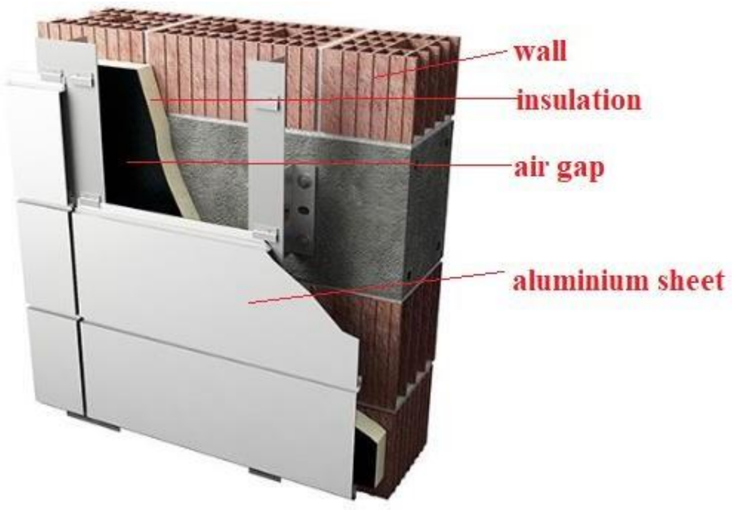



**Figure 7.** *Alucovering* ventilated façade system (*Aliva*). [16]


**Figure 8.** Constructive elements of *Alucovering* ventilated façade system (*Aliva*). [16]

The overall data on materials relating to each façade are reported; the material quantities are divided into three groups: structure, cladding and window outline (Tables from 5 to 11).

| | aluminum alloy | steel | PVC | resin | polyurethane |
|---|---|---|---|---|---|
| D1 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 471,15 | | | | |
| anchor rod HIT-V M8 | | 64,73 | | | |
| resin HIT-HY 170 | | | | 8,53 | |
| thermostop | | | 79,15 | | |
| TL rivet | 4,04 | | | | |
| T mullion | 483,58 | | | | |
| D1 cladding | | | | | |
| Alucovering cladding profile | 6250,74 | | | | |
| TL rivet | 12,17 | | | | |
| retaining clip | 157,37 | | | | |
| metal profile | 42,68 | | | | |
| insulating material | | | | | 3151,09 |
| EJOT H3 wall anchor | | | 23,64 | | |
| D1 windows | | | | | |
| insulating material | | | | | 143,11 |
| EJOT H3 wall anchor | | | 7,70 | | |
| sheet metal | 1407,47 | | | | |
| TL rivet | 1,30 | | | | |
| anchor rod HIT-V M8 | | 18,18 | | | |
| resin HIT-HY 170 | | | | 2,40 | |
| Total | 8830,49 | 82,91 | 110,50 | 10,93 | 3294,20 |

**Table 5.** Ventilated façade D1.

| | aluminum alloy | steel | PVC | resin | polyurethane |
|---|---|---|---|---|---|
| D2 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 621,87 | | | | |
| anchor rod HIT-V M8 | | 54,47 | | | |
| resin HIT-HY 170 | | | | 11,23 | |
| thermostop | | | 79,15 | | |
| TL rivet | 4,48 | | | | |
| T mullion | 638,13 | | | | |
| D2 cladding | | | | | |
| Alucovering cladding profile | 8002,09 | | | | |
| TL rivet | 13,81 | | | | |
| retaining clip | 178,56 | | | | |
| metal profile | 51,49 | | | | |
| insulating material | | | | | 4033,97 |
| EJOT H3 wall anchor | | | 30,27 | | |
| D2 windows | | | | | |
| insulating material | | | | | 170,48 |
| EJOT H3 wall anchor | | | 9,25 | | |
| sheet metal | 1671,68 | | | | |
| TL rivet | 1,54 | | | | |
| anchor rod HIT-V M8 | | 21,84 | | | |
| resin HIT-HY 170 | | | | 2,88 | |
| Total | 11183,64 | 76,31 | 118,67 | 14,11 | 4204,45 |

**Table 6.** Ventilated façade D2.

| | aluminum alloy | steel | PVC | resin | polyurethane |
|---|---|---|---|---|---|
| D3 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 48,6 | | | | |
| anchor rod HIT-V M8 | | 6,81696 | | | |
| resin HIT-HY 170 | | | | 0,898791 | |
| thermostop | | | 8,1648 | | |
| TL rivet | 0,324 | | | | |
| T mullion | 21,576 | | | | |
| D3 cladding | | | | | |
| Alucovering cladding profile | 1024,8768 | | | | |
| TL rivet | 0,99 | | | | |
| retaining clip | 12,804 | | | | |
| metal profile | 4,6754 | | | | |
| insulating material | | | | | 516,656 |
| EJOT H3 wall anchor | | | 3,87677 | | |
| Total | 1113,8462 | 6,81696 | 12,0416 | 0,898791 | 516,656 |

**Table 7.** Ventilated façade D3.

| | aluminum alloy | steel | PVC | resin | polyurethane |
|---|---|---|---|---|---|
| D4 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 61,35 | | | | |
| anchor rod HIT-V M8 | | 8,46 | | | |
| resin HIT-HY 170 | | | | 1,12 | |
| thermostop | | | 10,31 | | |
| TL rivet | 0,51 | | | | |
| T mullion | 64,95 | | | | |
| D4 cladding | | | | | |
| Alucovering cladding profile | 442,16 | | | | |
| TL rivet | 1,49 | | | | |
| retaining clip | 19,32 | | | | |
| metal profile | 2,68 | | | | |
| insulating material | | | | | 222,90 |
| EJOT H3 wall anchor | | | 1,67 | | |
| D4 windows | | | | | |
| insulating material | | | | | 11,93 |
| EJOT H3 wall anchor | | | 0,64 | | |
| sheet metal | 117,29 | | | | |
| TL rivet | 0,11 | | | | |
| anchor rod HIT-V M8 | | 1,51 | | | |
| resin HIT-HY 170 | | | | 0,20 | |
| Total | 709,86 | 9,97 | 12,62 | 1,31 | 234,83 |

**Table 8.** Ventilated façade D4.

| | aluminum alloy | steel | PVC | resin | polyurethane |
|---|---|---|---|---|---|
| D5 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 160,14 | | | | |
| anchor rod HIT-V M8 | | 22,22 | | | |
| resin HIT-HY 170 | | | | 2,93 | |
| thermostop | | | 26,90 | | |
| TL rivet | 1,23 | | | | |
| T mullion | 155,78 | | | | |
| D5 cladding | | | | | |
| Alucovering cladding profile | 1208,20 | | | | |
| TL rivet | 3,70 | | | | |
| retaining clip | 47,80 | | | | |
| metal profile | 6,83 | | | | |
| insulating material | | | | | 609,07 |
| EJOT H3 wall anchor | | | 4,57 | | |
| D5 windows | | | | | |
| insulating material | | | | | 23,85 |
| EJOT H3 wall anchor | | | 1,28 | | |
| sheet metal | 234,58 | | | | |
| TL rivet | 0,22 | | | | |
| anchor rod HIT-V M8 | | 3,03 | | | |
| resin HIT-HY 170 | | | | 0,40 | |
| Total | 1818,47 | 25,25 | 32,76 | 3,33 | 632,92 |

**Table 9.** Ventilated façade D5.

| | aluminum alloy | steel | PVC | resin | polyurethane |
|---|---|---|---|---|---|
| D6 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 32,40 | | | | |
| anchor rod HIT-V M8 | | 4,54 | | | |
| resin HIT-HY 170 | | | | 0,60 | |
| thermostop | | | 5,44 | | |
| TL rivet | 0,22 | | | | |
| T mullion | 25,89 | | | | |
| D6 cladding | | | | | |
| Alucovering cladding profile | 301,90 | | | | |
| TL rivet | 0,66 | | | | |
| retaining clip | 8,54 | | | | |
| metal profile | 1,38 | | | | |
| insulating material | | | | | 152,19 |
| EJOT H3 wall anchor | | | 1,14 | | |
| Total | 370,98 | 4,54 | 6,59 | 0,60 | 152,19 |

**Table 10.** Ventilated façade D6.

| | aluminum alloy | steel | PVC | resin | polyurethane |
|---|---|---|---|---|---|
| D7 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 578,97 | | | | |
| anchor rod HIT-V M8 | | 79,69 | | | |
| resin HIT-HY 170 | | | | 8,53 | |
| thermostop | | | 85,35 | | |
| TL rivet | 4,24 | | | | |
| T mullion | 621,97 | | | | |
| D7 cladding | | | | | |
| Alucovering cladding profile | 4967,29 | | | | |
| TL rivet | 15,71 | | | | |
| retaining clip | 203,23 | | | | |
| metal profile | 27,92 | | | | |
| insulating material | | | | | 2504,09 |
| EJOT H3 wall anchor | | | 18,79 | | |
| D7 windows | | | | | |
| insulating material | | | | | 96,74 |
| EJOT H3 wall anchor | | | 5,45 | | |
| sheet metal | 937,71 | | | | |
| TL rivet | 0,92 | | | | |
| anchor rod HIT-V M8 | | 12,88 | | | |
| resin HIT-HY 170 | | | | 1534,08 | |
| Total | 7357,97 | 92,57 | 109,60 | 1542,61 | 2600,83 |

**Table 11.** Ventilated façade D7.

The total quantities of each material are summarized in Table 12 and graphed in Figure 9.

| façade | aluminum alloy | steel | PVC | resin | polyurethane |
|---|---|---|---|---|---|
| D1 | 8830,49 | 82,91 | 110,50 | 10,93 | 3294,20 |
| D2 | 11183,64 | 76,31 | 118,67 | 14,11 | 4204,45 |
| D3 | 1113,85 | 6,82 | 12,04 | 0,90 | 516,66 |
| D4 | 709,86 | 9,97 | 12,62 | 1,31 | 234,83 |
| D5 | 1818,47 | 25,25 | 32,76 | 3,33 | 632,92 |
| D6 | 370,98 | 4,54 | 6,59 | 0,60 | 152,19 |
| D7 | 7357,97 | 92,57 | 109,60 | 1542,61 | 2600,83 |
| total | 31385,26 | 298,37 | 402,78 | 1573,80 | 11636,08 |

**Table 12.** Total quantities of each material for case1-ventilated façade-polyurethane (insulation).

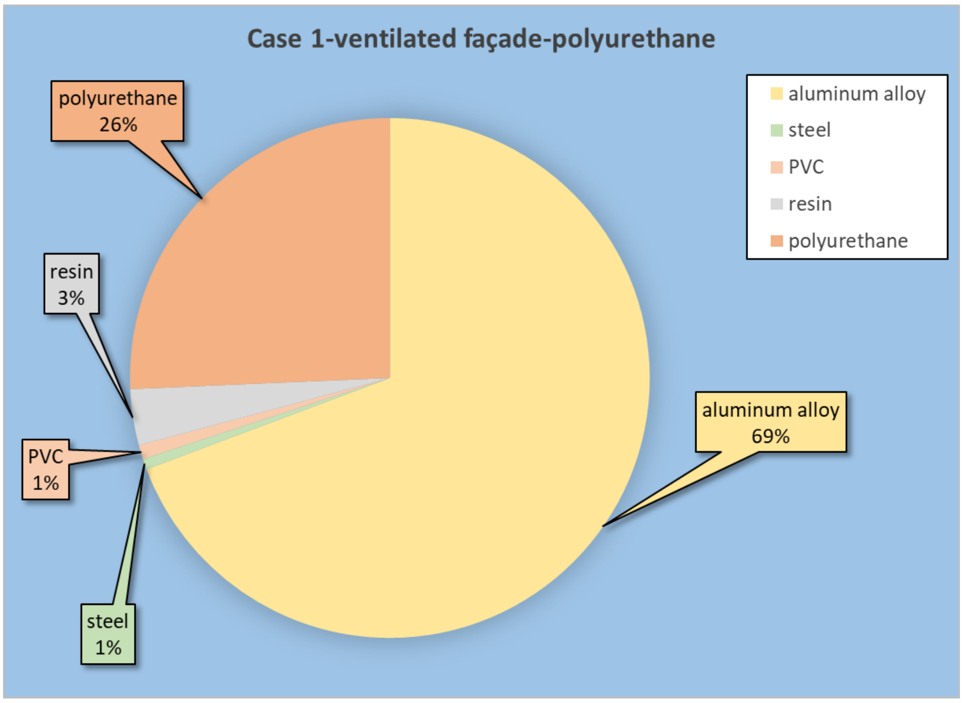



**Figure 9.** Pie chart of the materials used in case 1-ventilated façade-polyurethane (insulation).

### 2.1.3 CASE 2-THERMAL COATING-ROCK WOOL (insulation)

In this case, the facades are covered with a rock wall thermal coat; the thickness of the rock wool insulation is calculated in such a way as to obtain the *thermal transmittance* U [W/($m^2$ K)] of case 1-thermal coating-polyurethane (Table 13).

| Thermal coating | λ [W/(m K)] | s [m] | U [W/(m2 K)] |
|---|---|---|---|
| polyurethane | 0,026 | 0,089 | 0,292 |
| rock wool | 0,034 | 0,116 | 0,292 |

**Table 13.** Thermal transmittance of the insulation.

The following tables contain the quantities of materials necessary for the thermal coating of the façades and the windows' outline (Tables 14 and 15).

| | | | | | D1 | D2 | D3 | D4 | D5 | D6 | D7 | total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | [m2] | [m2] | [m2] | [m2] | [m2] | [m2] | [m2] | [m2] |
| | | | | | 643,08 | 823,26 | 105,44 | 45,49 | 124,30 | 31,06 | 511,04 | 2283,67 |
| element | material | | | [kg/m2] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] |
| Klebocem adhesive | cement | | | 4,5 | 2893,87 | 3704,68 | 474,50 | 204,71 | 559,34 | 139,78 | 2299,67 | 10276,54 |
| | | [kg/m3] | thickness [m] | | | | | | | | | |
| Insulation | rock wool | 40 | 0,116 | 4,64 | 2983,90 | 3819,93 | 489,26 | 211,08 | 576,74 | 144,13 | 2371,22 | 10596,25 |
| | | [kg/el] | [el/m2] | | | | | | | | | |
| EJOT H3 wall anchor | PVC | 0,01337 | 6 | 0,0802 | 51,59 | 66,04 | 8,46 | 3,65 | 9,97 | 2,49 | 41,00 | 183,20 |
| Klebocem skim coat | cement | | | 4,5 | 2893,87 | 3704,68 | 474,50 | 204,71 | 559,34 | 139,78 | 2299,67 | 10276,54 |
| | | [kg/m2] | [el/m2] | | | | | | | | | |
| Armatex C1 mesh | glass fiber | 0,15 | 1,1 | 0,165 | 106,11 | 135,84 | 17,40 | 7,51 | 20,51 | 5,13 | 84,32 | 376,81 |
| RivatonePlus finish coat | acrylic resin | | | 3 | 1929,25 | 2469,78 | 316,33 | 136,47 | 372,89 | 93,19 | 1533,11 | 6851,02 |

**Table 14.** Façades' thermal coating.

| | | | | | | D1 | D2 | D2 | D2 | D3 | D4 | D5 | D6 | D7 | D7 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | window height | [m] | 1,55 | 1,55 | 2,19 | 2,33 | 0,00 | 1,55 | 1,55 | 0,00 | 1,55 | 1,62 | |
| | | | | window base | [m] | 1,61 | 1,61 | 1,35 | 1,84 | 0,00 | 1,61 | 1,61 | 0,00 | 1,61 | 0,80 | |
| | | | | window depth | [m] | 0,30 | 0,30 | 0,30 | 0,30 | 0,00 | 0,30 | 0,30 | 0,00 | 0,30 | 0,30 | |
| | | | | window otline surface | [m2] | 1,89 | 1,89 | 2,12 | 2,50 | 0,00 | 1,89 | 1,89 | 0,00 | 1,89 | 1,45 | |
| | | | | # windows | | 72,00 | 82,00 | 1,00 | 2,00 | 0,00 | 6,00 | 12,00 | 0,00 | 41,00 | 10,00 | |
| | | | | total contour surface | [m2] | 136,30 | 155,23 | 2,12 | 5,01 | 0,00 | 11,36 | 22,72 | 0,00 | 77,61 | 14,52 | |
| element | material | | | [kg/m2] | | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] |
| Klebocem adhesive | cement | | | 5 | | 681,48 | 776,13 | 10,62 | 25,04 | 0,00 | 56,79 | 113,58 | 0,00 | 388,07 | 72,60 | 1736,25 |
| | | [kg/m3] | thickness [m] | | | | | | | | | | | | | |
| Insulation | rock wool | 40 | 0,04 | 1,6 | | 218,07 | 248,36 | 3,40 | 8,01 | 0,00 | 18,17 | 36,35 | 0,00 | 124,18 | 23,23 | 299,22 |
| | | [kg/el] | [el/m2] | | | | | | | | | | | | | |
| EJOT H3 wall anchor | PVC | 0,0134 | 6 | 0,08022 | | 10,93 | 12,45 | 0,17 | 0,40 | 0,00 | 0,91 | 1,82 | 0,00 | 6,23 | 1,16 | 15,00 |
| Klebocem skim coat | cement | | | 5 | | 681,48 | 776,13 | 10,62 | 25,04 | 0,00 | 56,79 | 113,58 | 0,00 | 388,07 | 72,60 | 935,07 |
| | | [kg/m2] | [el/m2] | | | | | | | | | | | | | |
| Armatex C1 mesh | glass fiber | 0,15 | 1,1 | 0,165 | | 22,49 | 25,61 | 0,35 | 0,83 | 0,00 | 1,87 | 3,75 | 0,00 | 12,81 | 2,40 | 30,86 |
| RivatonePlus finish coat | acrylic resin | | | 2,2 | | 299,85 | 341,50 | 4,67 | 11,02 | 0,00 | 24,99 | 49,98 | 0,00 | 170,75 | 31,94 | 411,43 |

**Table 15.** Thermal coating for windows' outline

The total quantities of each material are summarized in Table 16 and graphed in Figure 10.

| | material | total |
|---|---|---|
| | | [kg] |
| Klebocem | cement | 23224,39 |
| Insulation | rock wool | 10895,47 |
| EJOT H3 wall anchor | PVC | 198,20 |
| Armatex C1 mesh | glass fiber | 407,66 |
| RivatonePlus finish coat | acrylic resin | 7262,46 |

**Table 16.** Total quantities of each material for case 2-thermal coating-rock wool (insulation).

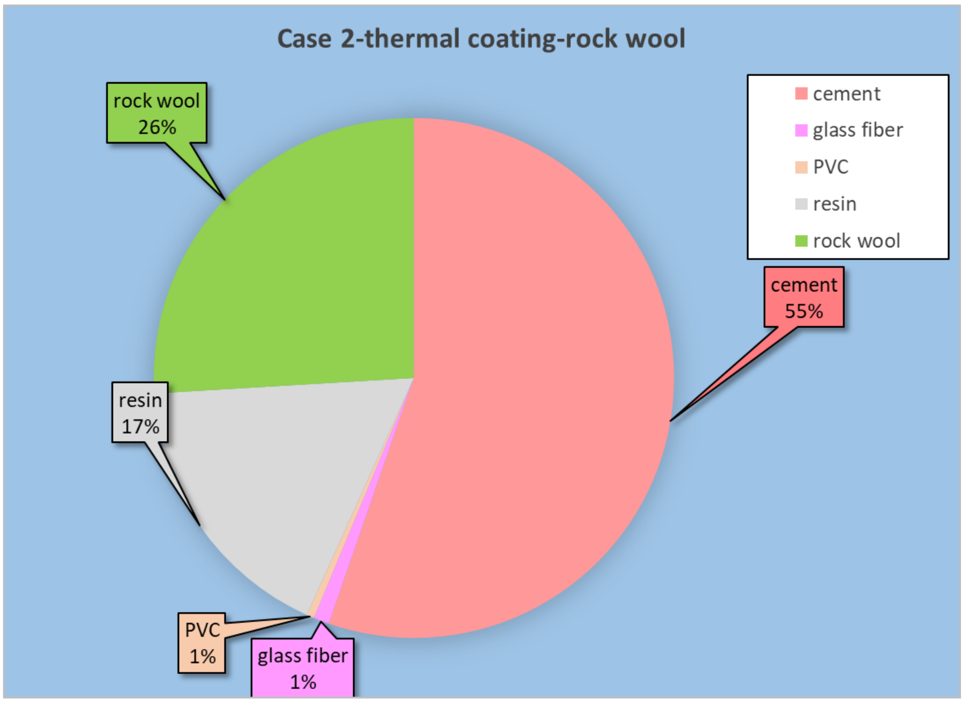



**Figure 10.** Pie chart of the materials used in case 2-themal coating-rock wool (insulation).

### 2.1.4 CASE 2-THERMAL COATING-GLASS WOOL (insulation)

In this case, the facades are covered with a glass wall thermal coat; the thickness of the glass wool insulation is calculated in such a way as to obtain the *thermal transmittance* U [W/(m$^2$ K)] of case 1-thermal coating-polyurethane (Table 17).

| Thermal coating | λ [W/(m K)] | s [m] | U [W/(m2 K)] |
|---|---|---|---|
| polyurethane | 0,026 | 0,089 | 0,292 |
| glass wool | 0,034 | 0,116 | 0,292 |

**Table 17.** Thermal transmittance of the insulation.

The following tables contain the quantities of materials necessary for the thermal coating of the façades and the windows' outline (Tables 18 and 19).

| | | | | | D1 | D2 | D3 | D4 | D5 | D6 | D7 | total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | [m2] | [m2] | [m2] | [m2] | [m2] | [m2] | [m2] | [m2] |
| | | | | | 643,08 | 823,26 | 105,44 | 45,49 | 124,30 | 31,06 | 511,04 | 2283,67 |
| element | material | | | [kg/m2] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] |
| Klebocem adhesive | cement | | | 4,5 | 2893,87 | 3704,68 | 474,50 | 204,71 | 559,34 | 139,78 | 2299,67 | 10276,54 |
| | | [kg/m3] | thickness [m] | | | | | | | | | |
| Insulation | glass wool | 16 | 0,116 | 1,856 | 1193,56 | 1527,97 | 195,70 | 84,43 | 230,70 | 57,65 | 948,49 | 4238,50 |
| | | [kg/el] | [el/m2] | | | | | | | | | |
| EJOT H3 wall anchor | PVC | 0,01337 | 6 | 0,0802 | 51,59 | 66,04 | 8,46 | 3,65 | 9,97 | 2,49 | 41,00 | 183,20 |
| Klebocem skim coat | cement | | | 4,5 | 2893,87 | 3704,68 | 474,50 | 204,71 | 559,34 | 139,78 | 2299,67 | 10276,54 |
| | | [kg/m2] | [el/m2] | | | | | | | | | |
| Armatex C1 mesh | glass fiber | 0,15 | 1,1 | 0,165 | 106,11 | 135,84 | 17,40 | 7,51 | 20,51 | 5,13 | 84,32 | 376,81 |
| RivatonePlus finish coat | acrylic resin | | | 3 | 1929,25 | 2469,78 | 316,33 | 136,47 | 372,89 | 93,19 | 1533,11 | 6851,02 |

**Table 18.** Façades' thermal coating.

| | | | | | | D1 | D2 | D2 | D2 | D3 | D4 | D5 | D6 | D7 | D7 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | window height | [m] | 1,55 | 1,55 | 2,19 | 2,33 | 0,00 | 1,55 | 1,55 | 0,00 | 1,55 | 1,62 | |
| | | | | window base | [m] | 1,61 | 1,61 | 1,35 | 1,84 | 0,00 | 1,61 | 1,61 | 0,00 | 1,61 | 0,80 | |
| | | | | window depth | [m] | 0,30 | 0,30 | 0,30 | 0,30 | 0,00 | 0,30 | 0,30 | 0,00 | 0,30 | 0,30 | |
| | | | | window outline surface | [m2] | 1,89 | 1,89 | 2,12 | 2,50 | 0,00 | 1,89 | 1,89 | 0,00 | 1,89 | 1,45 | |
| | | | | # windows | | 72,00 | 82,00 | 1,00 | 2,00 | 0,00 | 6,00 | 12,00 | 0,00 | 41,00 | 10,00 | |
| | | | | total contour surface | [m2] | 136,30 | 155,23 | 2,12 | 5,01 | 0,00 | 11,36 | 22,72 | 0,00 | 77,61 | 14,52 | |
| element | material | | | [kg/m2] | | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | | [kg] | [kg] |
| Klebocem adhesive | cement | | | 5 | | 681,48 | 776,13 | 10,62 | 25,04 | 0,00 | 56,79 | 113,58 | 0,00 | 388,07 | 72,60 | 1736,25 |
| | | [kg/m3] | thickness [m] | | | | | | | | | | | | | |
| Insulation | glass wool | 16 | 0,04 | 0,64 | | 87,23 | 99,34 | 1,36 | 3,21 | 0,00 | 7,27 | 14,54 | 0,00 | 49,67 | 9,29 | 119,69 |
| | | [kg/cad] | [el/m2] | | | | | | | | | | | | | |
| EJOT H3 wall anchor | PVC | 0,01337 | 6 | 0,08022 | | 10,93 | 12,45 | 0,17 | 0,40 | 0,00 | 0,91 | 1,82 | 0,00 | 6,23 | 1,16 | 15,00 |
| Klebocem skim coat | cement | | | 5 | | 681,48 | 776,13 | 10,62 | 25,04 | 0,00 | 56,79 | 113,58 | 0,00 | 388,07 | 72,60 | 935,07 |
| | | [kg/m2] | [el/m2] | | | | | | | | | | | | | |
| Armatex C1 mesh | glass fiber | 0,15 | 1,1 | 0,165 | | 22,49 | 25,61 | 0,35 | 0,83 | 0,00 | 1,87 | 3,75 | 0,00 | 12,81 | 2,40 | 30,86 |
| RivatonePlus finish coat | acrylic resin | | | 2,2 | | 299,85 | 341,50 | 4,67 | 11,02 | 0,00 | 24,99 | 49,98 | 0,00 | 170,75 | 31,94 | 411,43 |

**Table 19.** Thermal coating for windows’ outline.

The total quantities of each material are summarized in Table 20 and graphed in Figure 11.

| | material | total |
|---|---|---|
| | | [kg] |
| Klebocem | cement | 23224,39 |
| Insulation | glass wool | 4358,19 |
| EJOT H3 wall anchor | PVC | 198,20 |
| Armatex C1 mesh | glass fiber | 407,66 |
| RivatonePlus finish coat | acrylic resin | 7262,46 |

**Table 20.** Total quantities of each material for case 2-thermal coating-rock wool (insulation).

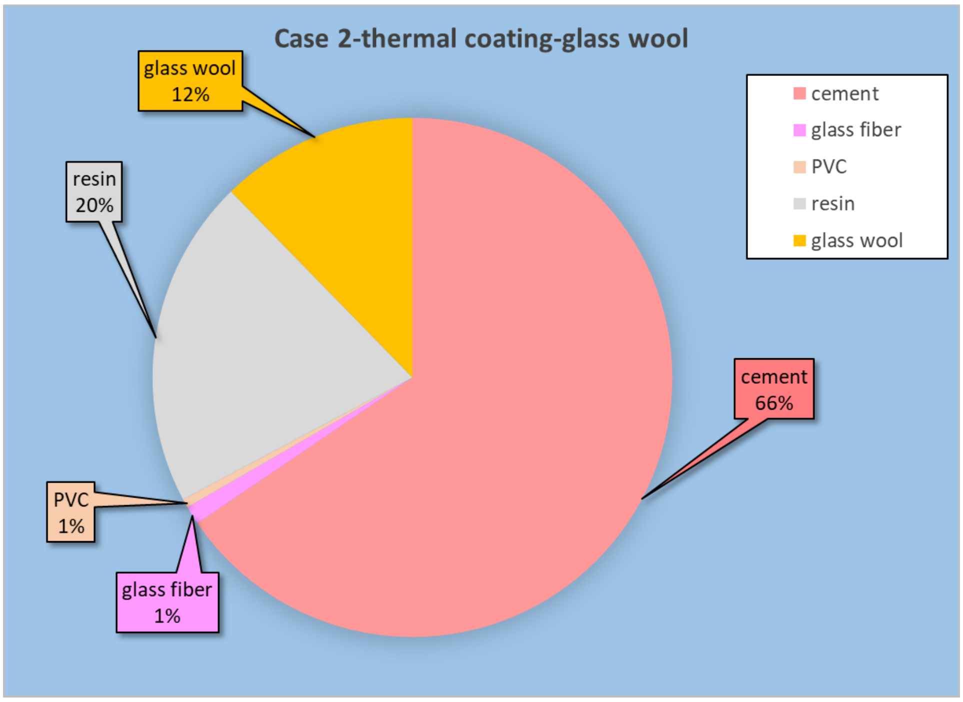



**Figure 11.** Pie chart of the materials used in case 2-themal coating-rock wool (insulation).

### 2.1.5 CASE 2-VENTILATED FAÇADE-ROCK WOOL (insulation)

In this case, the redevelopment of the building consists of ventilated façade wall cladding using rock wool as insulation and sheets of aluminium alloy as cladding. The thickness of the rock wool insulation is calculated in such a way as to obtain the *thermal transmittance* U [W/(m$^2$ K)] of case 1-ventilated façade-polyurethane (Table 22).

| Thermal coating | λ [W/(m K)] | s [m] | U [W/(m2 K)] |
|---|---|---|---|
| polyurethane | 0,026 | 0,14 | 0,186 |
| rock wool | 0,034 | 0,183 | 0,186 |

**Table 22.** Thermal transmittance of the insulation.

The overall data on materials relating to each façade are reported; the material quantities are divided into three groups: structure, cladding and window outline (Tables from 23 to 29).

| | aluminum alloy | steel | PVC | resin | rock wool |
|---|---|---|---|---|---|
| D1 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 607,69 | | | | |
| anchor rod HIT-V M8 | | 64,73 | | | |
| resin HIT-HY 170 | | | | 8,53 | |
| thermostop | | | 79,15 | | |
| TL rivet | 4,04 | | | | |
| T mullion | 483,58 | | | | |
| D1 cladding | | | | | |
| Alucovering cladding profile | 6250,74 | | | | |
| TL rivet | 12,17 | | | | |
| retaining clip | 157,37 | | | | |
| metal profile | 42,68 | | | | |
| insulating material | | | | | 4707,35 |
| EJOT H3 wall anchor | | | 23,64 | | |
| D1 windows | | | | | |
| insulating material | | | | | 218,07 |
| EJOT H3 wall anchor | | | 7,70 | | |
| sheet metal | 1407,47 | | | | |
| TL rivet | 1,30 | | | | |
| anchor rod HIT-V M8 | | 18,18 | | | |
| resin HIT-HY 170 | | | | 2,40 | |
| Total | 8967,03 | 82,91 | 110,50 | 10,93 | 4925,42 |

**Table 23.** Ventilated façade D1.

| | aluminum alloy | steel | PVC | resin | rock wool |
|---|---|---|---|---|---|
| D2 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 802,17 | | | | |
| anchor rod HIT-V M8 | | 54,47 | | | |
| resin HIT-HY 170 | | | | 11,23 | |
| thermostop | | | 79,15 | | |
| TL rivet | 4,48 | | | | |
| T mullion | 638,13 | | | | |
| D2 cladding | | | | | |
| Alucovering cladding profile | 8002,09 | | | | |
| TL rivet | 13,81 | | | | |
| retaining clip | 178,56 | | | | |
| metal profile | 51,49 | | | | |
| insulating material | | | | | 6026,26 |
| EJOT H3 wall anchor | | | 30,27 | | |
| D2 windows | | | | | |
| insulating material | | | | | 259,78 |
| EJOT H3 wall anchor | | | 9,25 | | |
| sheet metal | 1671,68 | | | | |
| TL rivet | 1,54 | | | | |
| anchor rod HIT-V M8 | | 21,84 | | | |
| resin HIT-HY 170 | | | | 2,88 | |
| Total | 11363,94 | 76,31 | 118,67 | 14,11 | 6286,04 |

**Table 24.** Ventilated façade D2.

| | aluminum alloy | steel | PVC | resin | rock wool |
|---|---|---|---|---|---|
| D3 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 62,64 | | | | |
| anchor rod HIT-V M8 | | 6,82 | | | |
| resin HIT-HY 170 | | | | 0,90 | |
| thermostop | | | 8,16 | | |
| TL rivet | 0,32 | | | | |
| T mullion | 21,58 | | | | |
| D3 cladding | | | | | |
| Alucovering cladding profile | 1024,88 | | | | |
| TL rivet | 0,99 | | | | |
| retaining clip | 12,80 | | | | |
| metal profile | 4,68 | | | | |
| insulating material | | | | | 771,82 |
| EJOT H3 wall anchor | | | 3,88 | | |
| Total | 1127,89 | 6,82 | 12,04 | 0,90 | 771,82 |

**Table 25.** Ventilated façade D3.

| | aluminum alloy | steel | PVC | resin | rock wool |
|---|---|---|---|---|---|
| D4 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 75,16 | | | | |
| anchor rod HIT-V M8 | | 8,46 | | | |
| resin HIT-HY 170 | | | | 1,12 | |
| thermostop | | | 10,31 | | |
| TL rivet | 0,51 | | | | |
| T mullion | 64,95 | | | | |
| D4 cladding | | | | | |
| Alucovering cladding profile | 442,16 | | | | |
| TL rivet | 1,49 | | | | |
| retaining clip | 19,32 | | | | |
| metal profile | 2,68 | | | | |
| insulating material | | | | | 332,99 |
| EJOT H3 wall anchor | | | 1,67 | | |
| D4 windows | | | | | |
| insulating material | | | | | 18,17 |
| EJOT H3 wall anchor | | | 0,64 | | |
| sheet metal | 117,29 | | | | |
| TL rivet | 0,11 | | | | |
| anchor rod HIT-V M8 | | 1,51 | | | |
| resin HIT-HY 170 | | | | 0,20 | |
| Total | 723,67 | 9,97 | 12,62 | 1,31 | 351,16 |

**Table 26.** Ventilated façade D4.

| | aluminum alloy | steel | PVC | resin | rock wool |
|---|---|---|---|---|---|
| D5 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 206,48 | | | | |
| anchor rod HIT-V M8 | | 22,22 | | | |
| resin HIT-HY 170 | | | | 2,93 | |
| thermostop | | | 26,90 | | |
| TL rivet | 1,23 | | | | |
| T mullion | 155,78 | | | | |
| D5 cladding | | | | | |
| Alucovering cladding profile | 1208,20 | | | | |
| TL rivet | 3,70 | | | | |
| retaining clip | 47,80 | | | | |
| metal profile | 6,83 | | | | |
| insulating material | | | | | 909,88 |
| EJOT H3 wall anchor | | | 4,57 | | |
| D5 windows | | | | | |
| insulating material | | | | | 36,35 |
| EJOT H3 wall anchor | | | 1,28 | | |
| sheet metal | 234,58 | | | | |
| TL rivet | 0,22 | | | | |
| anchor rod HIT-V M8 | | 3,03 | | | |
| resin HIT-HY 170 | | | | 0,40 | |
| Total | 1864,81 | 25,25 | 32,76 | 3,33 | 946,22 |

**Table 27.** Ventilated façade D5.

| | aluminum alloy | steel | PVC | resin | rock wool |
|---|---|---|---|---|---|
| D6 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 41,76 | | | | |
| anchor rod HIT-V M8 | | 4,54 | | | |
| resin HIT-HY 170 | | | | 0,60 | |
| thermostop | | | 5,44 | | |
| TL rivet | 0,22 | | | | |
| T mullion | 25,89 | | | | |
| D6 cladding | | | | | |
| Alucovering cladding profile | 301,90 | | | | |
| TL rivet | 0,66 | | | | |
| retaining clip | 8,54 | | | | |
| metal profile | 1,38 | | | | |
| insulating material | | | | | 227,36 |
| EJOT H3 wall anchor | | | 1,14 | | |
| Total | 380,34 | 4,54 | 6,59 | 0,60 | 227,36 |

**Table 28.** Ventilated façade D6.

| | aluminum alloy | steel | PVC | resin | rock wool |
|---|---|---|---|---|---|
| D7 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 746,71 | | | | |
| anchor rod HIT-V M8 | | 79,69 | | | |
| resin HIT-HY 170 | | | | 8,53 | |
| thermostop | | | 85,35 | | |
| TL rivet | 4,24 | | | | |
| T mullion | 621,97 | | | | |
| D7 cladding | | | | | |
| Alucovering cladding profile | 4967,29 | | | | |
| TL rivet | 15,71 | | | | |
| retaining clip | 203,23 | | | | |
| metal profile | 27,92 | | | | |
| insulating material | | | | | 3740,80 |
| EJOT H3 wall anchor | | | 18,79 | | |
| D7 windows | | | | | |
| insulating material | | | | | 147,41 |
| EJOT H3 wall anchor | | | 5,45 | | |
| sheet metal | 937,71 | | | | |
| TL rivet | 0,92 | | | | |
| anchor rod HIT-V M8 | | 12,88 | | | |
| resin HIT-HY 170 | | | | 1534,08 | |
| Total | 7525,71 | 92,57 | 109,60 | 1542,61 | 3888,21 |

**Table 29.** Ventilated façade D7.

The total quantities of each material are summarized in Table 30 and graphed in Figure 12.

| façade | aluminum alloy | steel | PVC | resin | rock wool |
|---|---|---|---|---|---|
| D1 | 8967,03 | 82,91 | 110,50 | 10,93 | 4925,42 |
| D2 | 11363,94 | 76,31 | 118,67 | 14,11 | 6286,04 |
| D3 | 1127,89 | 6,82 | 12,04 | 0,90 | 771,82 |
| D4 | 723,67 | 9,97 | 12,62 | 1,31 | 351,16 |
| D5 | 1864,81 | 25,25 | 32,76 | 3,33 | 946,22 |
| D6 | 380,34 | 4,54 | 6,59 | 0,60 | 227,36 |
| D7 | 7525,71 | 82,91 | 110,50 | 10,93 | 3888,21 |
| total | 31953,39 | 288,71 | 403,68 | 42,11 | 17396,23 |

**Table 30.** Total quantities of each material for case 2-ventilated façade-rock wool (insulation).

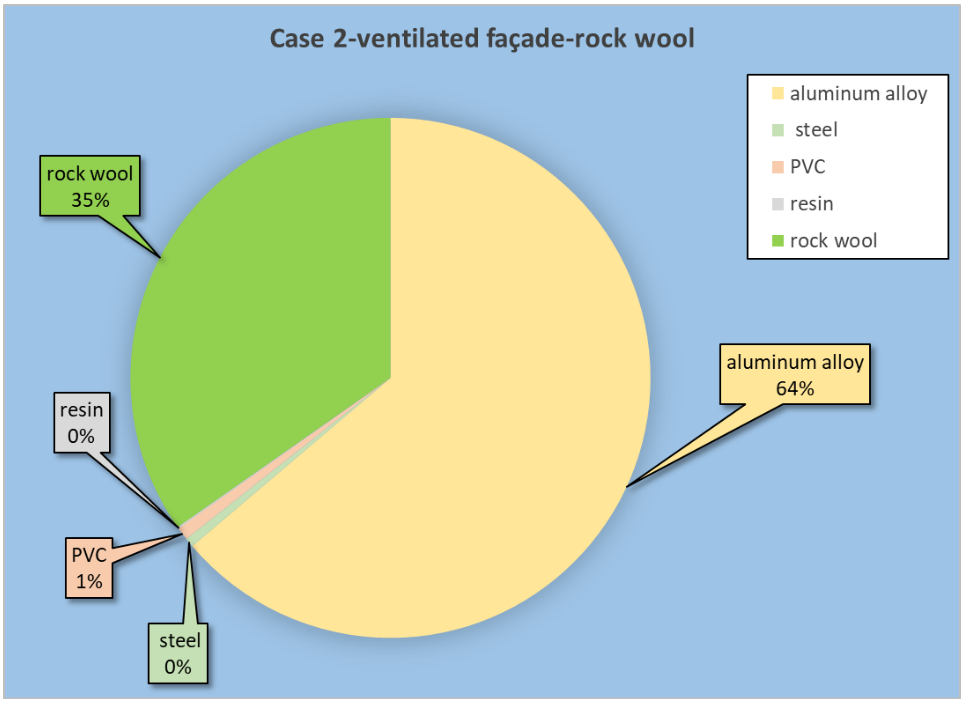



**Figure 12.** Pie chart of the materials used in case 2-ventilated façade-rock wool (insulation).

### 2.1.6 CASE 2-VENTILATED FAÇADE-GLASS WOOL (insulation)

In this case the upgrading of the building consists of ventilated façade wall cladding using glass wool as insulation and sheets of aluminium alloy as cladding. The thickness of the glass wool insulation is calculated in such a way as to obtain the *thermal transmittance* U [W/($m^2$ K)] of case 1-ventilated façade-polyurethane (Table 31).

| Thermal coating | λ [W/(m K)] | s [m] | U [W/(m2 K)] |
|---|---|---|---|
| polyurethane | 0,026 | 0,14 | 0,186 |
| glass wool | 0,034 | 0,183 | 0,186 |

**Table 31.** Thermal transmittance of the insulation.

The overall data on materials relating to each façade are reported; the material quantities are divided into three groups: structure, cladding and window outline (Tables from 32 to 38).

| | aluminum alloy | steel | PVC | resin | glass wool |
|---|---|---|---|---|---|
| D1 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 607,69 | | | | |
| anchor rod HIT-V M8 | | 64,73 | | | |
| resin HIT-HY 170 | | | | 8,53 | |
| thermostop | | | 79,15 | | |
| TL rivet | 4,04 | | | | |
| T mullion | 483,58 | | | | |
| D1 cladding | | | | | |
| Alucovering cladding profile | 6250,74 | | | | |
| TL rivet | 12,17 | | | | |
| retaining clip | 157,37 | | | | |
| metal profile | 42,68 | | | | |
| insulating material | | | | | 1882,94 |
| EJOT H3 wall anchor | | | 23,64 | | |
| D1 windows | | | | | |
| insulating material | | | | | 87,23 |
| EJOT H3 wall anchor | | | 7,70 | | |
| sheet metal | 1407,47 | | | | |
| TL rivet | 1,30 | | | | |
| anchor rod HIT-V M8 | | 18,18 | | | |
| resin HIT-HY 170 | | | | 2,40 | |
| Total | 8967,03 | 82,91 | 110,50 | 10,93 | 1970,17 |

**Table 32.** Ventilated façade D1.

| | aluminum alloy | steel | PVC | resin | glass wool |
|---|---|---|---|---|---|
| D2 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 802,17 | | | | |
| anchor rod HIT-V M8 | | 54,47 | | | |
| resin HIT-HY 170 | | | | 11,23 | |
| thermostop | | | 79,15 | | |
| TL rivet | 4,48 | | | | |
| T mullion | 638,13 | | | | |
| D2 cladding | | | | | |
| Alucovering cladding profile | 8002,09 | | | | |
| TL rivet | 13,81 | | | | |
| retaining clip | 178,56 | | | | |
| metal profile | 51,49 | | | | |
| insulating material | | | | | 2410,51 |
| EJOT H3 wall anchor | | | 30,27 | | |
| D2 windows | | | | | |
| insulating material | | | | | 103,91 |
| EJOT H3 wall anchor | | | 9,25 | | |
| sheet metal | 1671,68 | | | | |
| TL rivet | 1,54 | | | | |
| anchor rod HIT-V M8 | | 21,84 | | | |
| resin HIT-HY 170 | | | | 2,88 | |
| Total | 11363,94 | 76,31 | 118,67 | 14,11 | 2514,42 |

**Table 33.** Ventilated façade D2.

| | aluminum alloy | steel | PVC | resin | glass wool |
|---|---|---|---|---|---|
| D3 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 62,64 | | | | |
| anchor rod HIT-V M8 | | 6,82 | | | |
| resin HIT-HY 170 | | | | 0,90 | |
| thermostop | | | 8,16 | | |
| TL rivet | 0,32 | | | | |
| T mullion | 21,58 | | | | |
| D3 cladding | | | | | |
| Alucovering cladding profile | 1024,88 | | | | |
| TL rivet | 0,99 | | | | |
| retaining clip | 12,80 | | | | |
| metal profile | 4,68 | | | | |
| insulating material | | | | | 308,73 |
| EJOT H3 wall anchor | | | 3,88 | | |
| Total | 1127,89 | 6,82 | 12,04 | 0,90 | 308,73 |

**Table 34.** Ventilated façade D3.

| | aluminum alloy | steel | PVC | resin | glass wool |
|---|---|---|---|---|---|
| D4 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 75,16 | | | | |
| anchor rod HIT-V M8 | | 8,46 | | | |
| resin HIT-HY 170 | | | | 1,12 | |
| thermostop | | | 10,31 | | |
| TL rivet | 0,51 | | | | |
| T mullion | 64,95 | | | | |
| D4 cladding | | | | | |
| Alucovering cladding profile | 442,16 | | | | |
| TL rivet | 1,49 | | | | |
| retaining clip | 19,32 | | | | |
| metal profile | 2,68 | | | | |
| insulating material | | | | | 133,19 |
| EJOT H3 wall anchor | | | 1,67 | | |
| D4 windows | | | | | |
| insulating material | | | | | 7,27 |
| EJOT H3 wall anchor | | | 0,64 | | |
| sheet metal | 117,29 | | | | |
| TL rivet | 0,11 | | | | |
| anchor rod HIT-V M8 | | 1,51 | | | |
| resin HIT-HY 170 | | | | 0,20 | |
| Total | 723,67 | 9,97 | 12,62 | 1,31 | 140,46 |

**Table 35.** Ventilated façade D4.

| | aluminum alloy | steel | PVC | resin | glass wool |
|---|---|---|---|---|---|
| D5 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 206,48 | | | | |
| anchor rod HIT-V M8 | | 22,22 | | | |
| resin HIT-HY 170 | | | | 2,93 | |
| thermostop | | | 26,90 | | |
| TL rivet | 1,23 | | | | |
| T mullion | 155,78 | | | | |
| D5 cladding | | | | | |
| Alucovering cladding profile | 1208,20 | | | | |
| TL rivet | 3,70 | | | | |
| retaining clip | 47,80 | | | | |
| metal profile | 6,83 | | | | |
| insulating material | | | | | 363,95 |
| EJOT H3 wall anchor | | | 4,57 | | |
| D5 windows | | | | | |
| insulating material | | | | | 14,54 |
| EJOT H3 wall anchor | | | 1,28 | | |
| sheet metal | 234,58 | | | | |
| TL rivet | 0,22 | | | | |
| anchor rod HIT-V M8 | | 3,03 | | | |
| resin HIT-HY 170 | | | | 0,40 | |
| Total | 1864,81 | 25,25 | 32,76 | 3,33 | 378,49 |

**Table 36.** Ventilated façade D5.

| | aluminum alloy | steel | PVC | resin | glass wool |
|---|---|---|---|---|---|
| D6 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 41,76 | | | | |
| anchor rod HIT-V M8 | | 4,54 | | | |
| resin HIT-HY 170 | | | | 0,60 | |
| thermostop | | | 5,44 | | |
| TL rivet | 0,22 | | | | |
| T mullion | 25,89 | | | | |
| D6 cladding | | | | | |
| Alucovering cladding profile | 301,90 | | | | |
| TL rivet | 0,66 | | | | |
| retaining clip | 8,54 | | | | |
| metal profile | 1,38 | | | | |
| insulating material | | | | | 90,94 |
| EJOT H3 wall anchor | | | 1,14 | | |
| Total | 380,34 | 4,54 | 6,59 | 0,60 | 90,94 |

**Table 37.** Ventilated façade D6.

| | aluminum alloy | steel | PVC | resin | glass wool |
|---|---|---|---|---|---|
| D7 structure | [kg] | [kg] | [kg] | [kg] | [kg] |
| L bracket | 746,71 | | | | |
| anchor rod HIT-V M8 | | 79,69 | | | |
| resin HIT-HY 170 | | | | 8,53 | |
| thermostop | | | 85,35 | | |
| TL rivet | 4,24 | | | | |
| T mullion | 621,97 | | | | |
| D7 cladding | | | | | |
| Alucovering cladding profile | 4967,29 | | | | |
| TL rivet | 15,71 | | | | |
| retaining clip | 203,23 | | | | |
| metal profile | 27,92 | | | | |
| insulating material | | | | | 1496,32 |
| EJOT H3 wall anchor | | | 18,79 | | |
| D7 windows | | | | | |
| insulating material | | | | | 58,97 |
| EJOT H3 wall anchor | | | 5,45 | | |
| sheet metal | 937,71 | | | | |
| TL rivet | 0,92 | | | | |
| anchor rod HIT-V M8 | | 12,88 | | | |
| resin HIT-HY 170 | | | | 1534,08 | |
| Total | 7525,71 | 92,57 | 109,60 | 1542,61 | 1555,29 |

**Table 38.** Ventilated façade D7.

The total quantities of each material are summarized in Table 39 and graphed in Figure 13.

| façade | aluminum alloy | steel | PVC | resin | glass wool |
|---|---|---|---|---|---|
| D1 | 8967,03 | 82,91 | 110,50 | 10,93 | 1970,17 |
| D2 | 11363,94 | 76,31 | 118,67 | 14,11 | 2514,42 |
| D3 | 1127,89 | 6,82 | 12,04 | 0,90 | 308,73 |
| D4 | 723,67 | 9,97 | 12,62 | 1,31 | 140,46 |
| D5 | 1864,81 | 25,25 | 32,76 | 3,33 | 378,49 |
| D6 | 380,34 | 4,54 | 6,59 | 0,60 | 90,94 |
| D7 | 7525,71 | 82,91 | 110,50 | 10,93 | 1555,29 |
| total | 31953,39 | 288,71 | 403,68 | 42,11 | 6958,49 |

**Table 39.** Total quantities of each material for case 2-ventilated façade-glass wool (insulation).

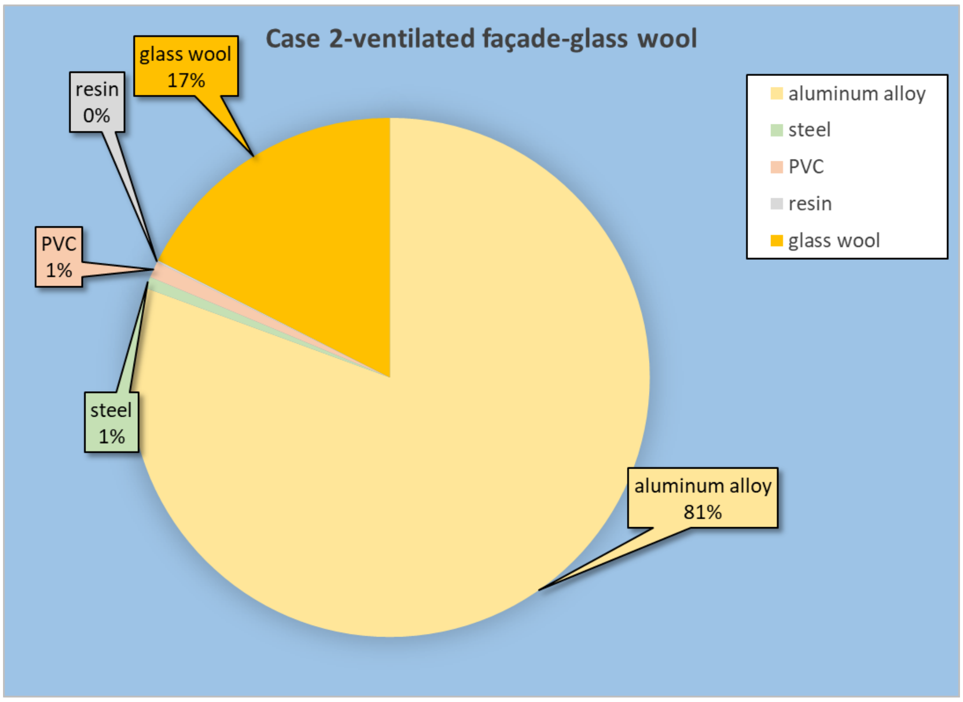



**Figure 13.** Pie chart of the materials used in case 2-ventilated façade-glass wool (insulation).

### 2.1.7 CASE 3-VENTILATED FAÇADE-PORCELAIN TILES (cladding)

In this case, the redevelopment of the building consists of ventilated façade wall cladding using polyurethane as insulation and porcelain tiles as cladding. The figures below (Figures 14 and 15) display the *Ali KL* (*Aliva*) ventilated façade system and his construction elements, as well as the substructure system.


**Figure 14.** *Ali KL* ventilated façade system (*Aliva*). [16]


**Figure 15.** Constructive elements of *Ali KL* ventilated façade system (*Aliva*). [16]

The following table (Table 40) contains the data about the construction materials for each façade. Tables about windows' outline materials are not reported because they are the same as case 1-ventilated façade-polyurethane.

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | D1 [m2] | D2 [m2] | D3 [m2] | D4 [m2] | D5 [m2] | D6 [m2] | D7 [m2] | total [m2] |
| | | | | | | | 643,08 | 823,26 | 105,44 | 45,49 | 124,30 | 31,06 | 511,04 | 2283,67 |
| element | material | [m3] | [kg/m3] | [kg] | Aref [m2] | [kg/m2ref] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | total [kg] |
| cladding | porcelain | 0,0072 | 2300 | 16,56 | 0,9248 | 17,906574 | 12451,78 | 15940,51 | 2041,66 | 880,82 | 2406,73 | 601,44 | 9895,05 | 44217,98 |
| | | # | [kg/el] | [kg] | Aref [m2] | [kg/m2ref] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | total [kg] |
| anchor rods HITVM8 | steel | 3 | 0,03156 | 0,095 | 0,9248 | 0,1023789 | 71,19 | 91,14 | 11,67 | 5,04 | 13,76 | 3,44 | 56,57 | 252,81 |
| | | # | [ml/el] | [ml] | Aref [m2] | [kg/m2ref] | [ml] | [ml] | [ml] | [ml] | [ml] | [ml] | [ml] | total [ml] |
| resin HIT-HY 170 | resin | 3 | 3,76 | 11,28 | 0,9248 | 12,197232 | 8481,65 | 10858,03 | 1390,70 | 599,98 | 1639,36 | 409,67 | 6740,11 | 30119,50 |
| | | # | [kg/el] | [kg] | Aref [m2] | [kg/m2ref] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | total [kg] |
| L bracket H150 | aluminum alloy | 1 | 0,45 | 0,45 | 0,9248 | 0,4865917 | 338,36 | 433,17 | 55,48 | 23,94 | 65,40 | 16,34 | 268,89 | 1201,58 |
| L bracket H80 | aluminum alloy | 1 | 0,24 | 0,24 | 0,9248 | 0,2595156 | 180,46 | 231,02 | 29,59 | 12,77 | 34,88 | 8,72 | 143,41 | 640,84 |
| | | # | lenght [m] | [kg/m] | Aref [m2] | [kg/m2ref] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | total [kg] |
| T1 mullion | aluminum alloy | 1 | 1,36 | 0,6 | 0,9248 | 0,8823529 | 613,57 | 785,47 | 100,60 | 43,40 | 118,59 | 29,64 | 487,58 | 2178,86 |
| | | # | [kg/el] | [kg] | Aref [m2] | [kg/m2ref] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | total [kg] |
| rivet | aluminum alloy | 9 | 0,0015 | 0,014 | 0,9248 | 0,0145978 | 10,15 | 12,99 | 1,66 | 0,72 | 1,96 | 0,49 | 8,07 | 36,05 |
| KL clip | steel | 2 | 0,287 | 0,574 | 0,9248 | 0,6206747 | 431,60 | 552,53 | 70,77 | 30,53 | 83,42 | 20,85 | 342,98 | 1532,68 |
| KL gasket | rubber | 4 | 0,0148 | 0,059 | 0,9248 | 0,0640138 | 44,51 | 56,99 | 7,30 | 3,15 | 8,60 | 2,15 | 35,37 | 158,07 |
| | | thickness [m] | [kg/m3] | | | [kg/m2] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | total [kg] |
| Insulation Stiferite | polyurethane | 0,14 | 35 | | | 4,9 | 3151,10 | 4033,98 | 516,67 | 222,90 | 609,06 | 152,20 | 2504,09 | 11190,01 |
| | | [kg/el] | [el/m2] | | | [kg/m2] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | total [kg] |
| EJOT H3 wall anchor | PVC | 0,01337 | 2,75 | | | 0,0367675 | 23,64 | 30,27 | 3,88 | 1,67 | 4,57 | 1,14 | 18,79 | 83,97 |

**Table 40.** Ventilated façades D1-D7.

The overall data on materials relating to each façade are reported in Table 41; the material quantities are divided into two groups: porcelain tiles, inclusive of their substructure, and windows' outline. The whole material amount is graphed in Figure 16.

| | aluminum alloy | steel | PVC | resin | polyurethane | porcelain | rubber |
|---|---|---|---|---|---|---|---|
| | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] | [kg] |
| D1 porcelain tiles ALI KL | 1142,541103 | 502,79328 | 23,6445 | 9,386385 | 3151,104823 | 12451,78 | 44,51361 |
| D1 windows | 1408,762886 | 18,17856 | 7,70112 | 2,396775 | 143,1108 | 0 | 0 |
| D2 porcelain tiles ALI KL | 1462,657571 | 30,269253 | 23,6445 | 12,01626 | 4033,979449 | 15940,51 | 56,98541 |
| D2 windows | 1673,226739 | 21,83952 | 9,25204 | 2,879459 | 170,47737 | 0 | 0 |
| D3 porcelain tiles ALI KL | 187,3373466 | 82,440761 | 3,87689 | 1,539044 | 516,6725424 | 2041,663 | 7,298698 |
| D3 windows | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| D4 porcelain tiles ALI KL | 80,82131031 | 35,566695 | 1,67257 | 0,663976 | 222,9035088 | 880,8166 | 3,148813 |
| D4 windows | 117,3969072 | 1,51488 | 0,64176 | 0,199731 | 11,9259 | 0 | 0 |
| D5 porcelain tiles ALI KL | 220,834533 | 97,181728 | 4,5701 | 1,814235 | 609,0570924 | 2406,726 | 8,603754 |
| D5 windows | 234,7938144 | 3,02976 | 1,28352 | 0,399463 | 23,8518 | 0 | 0 |
| D6 porcelain tiles ALI KL | 55,18615215 | 24,285539 | 1,14206 | 0,453374 | 152,2022707 | 601,4364 | 2,150063 |
| D6 windows | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| D7 porcelain tiles ALI KL | 907,9423853 | 399,5544 | 18,7896 | 7,459072 | 2504,086394 | 9895,048 | 35,3736 |
| D7 windows | 938,6319312 | 12,87648 | 5,45496 | 1534,08 | 96,73965 | 0 | 0 |
| total | 8430,13268 | 1229,5309 | 101,674 | 1573,288 | 11636,1116 | 44217,98 | 158,074 |

**Table 41.** Total quantities of each material for case 3-ventilated façade-porcelain tiles (cladding).

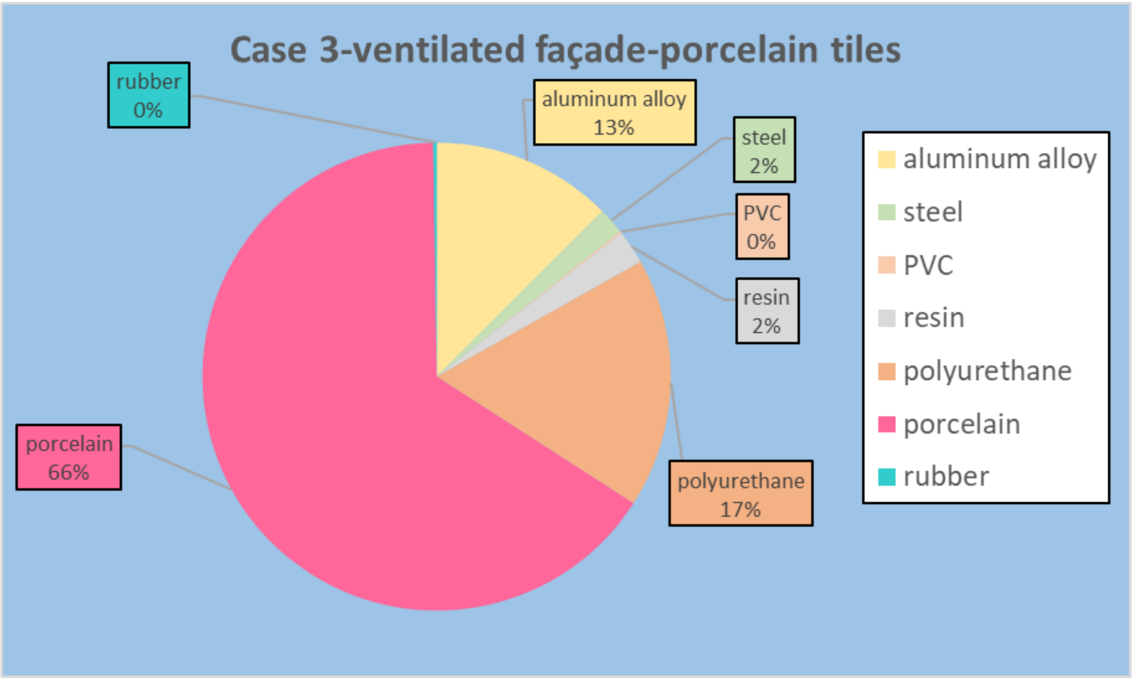
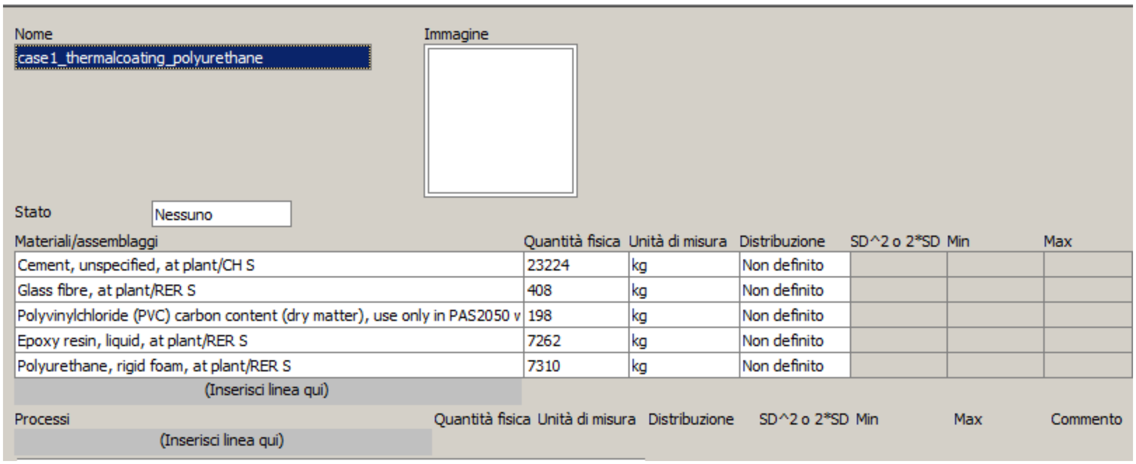



**Figure 16.** Pie chart of the materials used in case 3-ventilated façade-porcelain tiles (cladding).

## 2.2 ANALYSIS AND RESULTS

Below (Figures from 17 to 23), the scenarios previously described are entered in *SimaPro 7* software using *Ecoinvent* system and unit processes database.



Nome: case1_thermalcoating_polyurethane

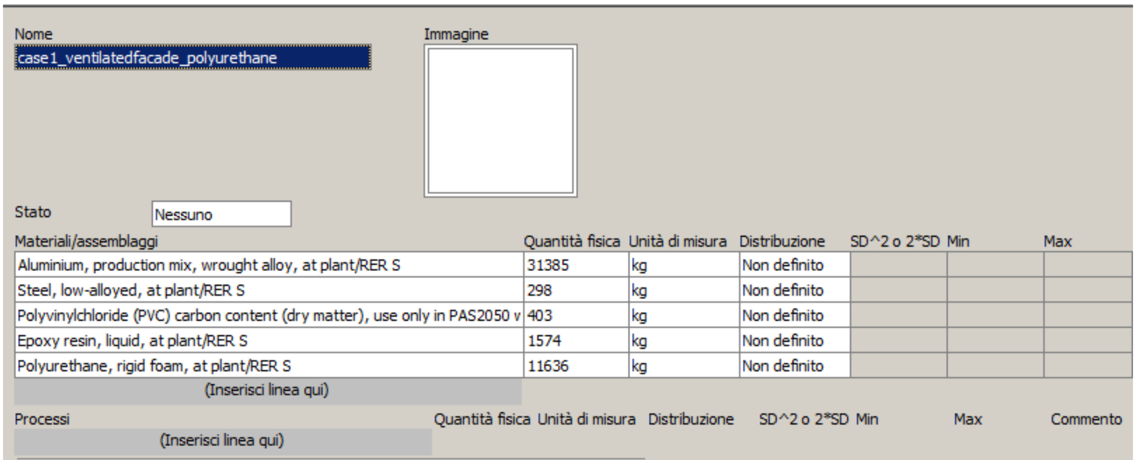
Immagine

Stato: Nessuno

| Materiali/assemblaggi | Quantità fisica | Unità di misura | Distribuzione | SD^2 o 2*SD | Min | Max |
|---|---|---|---|---|---|---|
| Cement, unspecified, at plant/CH S | 23224 | kg | Non definito | | | |
| Glass fibre, at plant/RER S | 408 | kg | Non definito | | | |
| Polyvinylchloride (PVC) carbon content (dry matter), use only in PAS2050 v | 198 | kg | Non definito | | | |
| Epoxy resin, liquid, at plant/RER S | 7262 | kg | Non definito | | | |
| Polyurethane, rigid foam, at plant/RER S | 7310 | kg | Non definito | | | |
| (Inserisci linea qui) | | | | | | |

| Processi | Quantità fisica | Unità di misura | Distribuzione | SD^2 o 2*SD | Min | Max | Commento |
|---|---|---|---|---|---|---|---|
| (Inserisci linea qui) | | | | | | | |

**Figure 17.** Case 1-thermal coating-polyurethane in *SimaPro*.



Nome: case1_ventilatedfacade_polyurethane

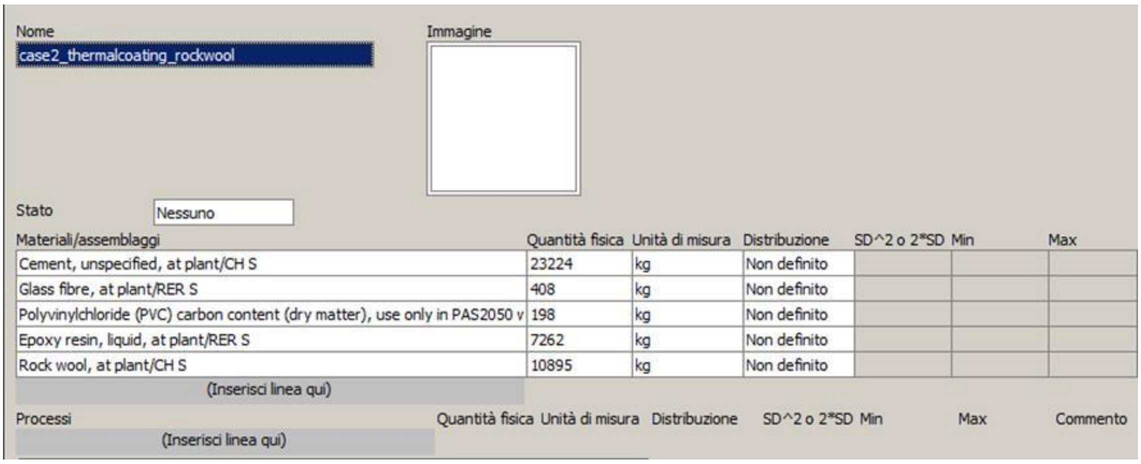
Immagine

Stato: Nessuno

| Materiali/assemblaggi | Quantità fisica | Unità di misura | Distribuzione | SD^2 o 2*SD | Min | Max |
|---|---|---|---|---|---|---|
| Aluminium, production mix, wrought alloy, at plant/RER S | 31385 | kg | Non definito | | | |
| Steel, low-alloyed, at plant/RER S | 298 | kg | Non definito | | | |
| Polyvinylchloride (PVC) carbon content (dry matter), use only in PAS2050 v | 403 | kg | Non definito | | | |
| Epoxy resin, liquid, at plant/RER S | 1574 | kg | Non definito | | | |
| Polyurethane, rigid foam, at plant/RER S | 11636 | kg | Non definito | | | |
| (Inserisci linea qui) | | | | | | |

| Processi | Quantità fisica | Unità di misura | Distribuzione | SD^2 o 2*SD | Min | Max | Commento |
|---|---|---|---|---|---|---|---|
| (Inserisci linea qui) | | | | | | | |

**Figure 18.** Case 1-ventilated façade-polyurethane in *SimaPro*.



Nome: case2_thermalcoating_rockwool

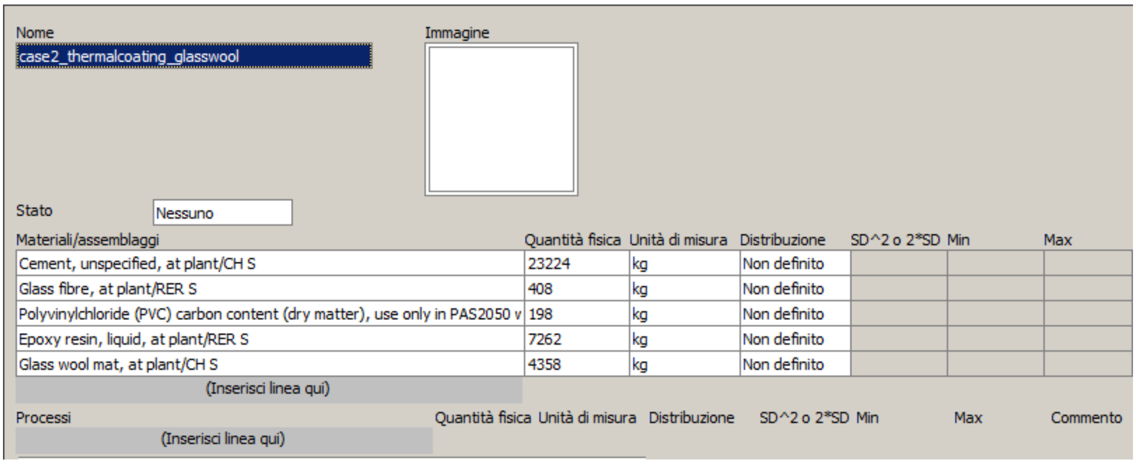
Immagine

Stato: Nessuno

| Materiali/assemblaggi | Quantità fisica | Unità di misura | Distribuzione | SD^2 o 2*SD | Min | Max |
|---|---|---|---|---|---|---|
| Cement, unspecified, at plant/CH S | 23224 | kg | Non definito | | | |
| Glass fibre, at plant/RER S | 408 | kg | Non definito | | | |
| Polyvinylchloride (PVC) carbon content (dry matter), use only in PAS2050 v | 198 | kg | Non definito | | | |
| Epoxy resin, liquid, at plant/RER S | 7262 | kg | Non definito | | | |
| Rock wool, at plant/CH S | 10895 | kg | Non definito | | | |
| (Inserisci linea qui) | | | | | | |

| Processi | Quantità fisica | Unità di misura | Distribuzione | SD^2 o 2*SD | Min | Max | Commento |
|---|---|---|---|---|---|---|---|
| (Inserisci linea qui) | | | | | | | |

**Figure 19.** Case 2-thermal coating-rock wool in *SimaPro*.



Nome: case2_thermalcoating_glasswool

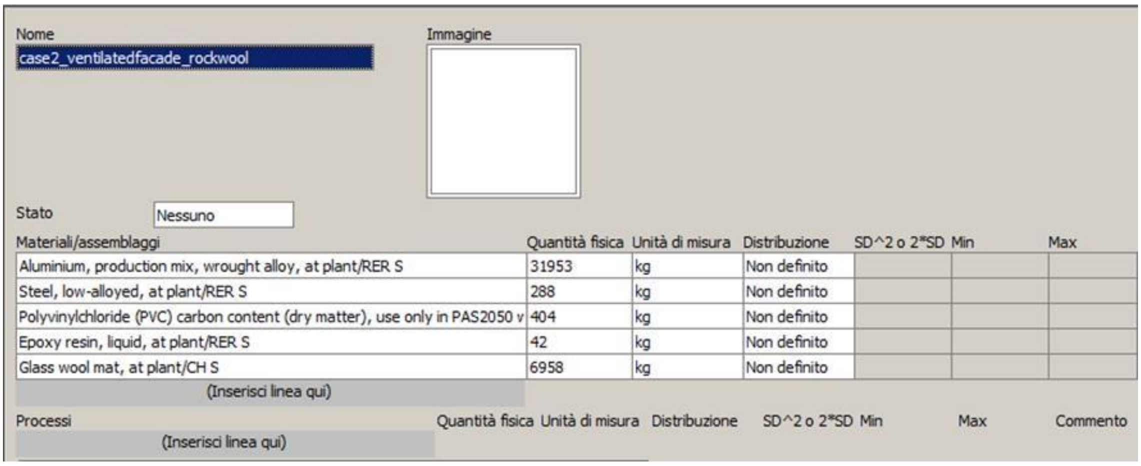
Immagine

Stato: Nessuno

| Materiali/assemblaggi | Quantità fisica | Unità di misura | Distribuzione | SD^2 o 2*SD | Min | Max |
|---|---|---|---|---|---|---|
| Cement, unspecified, at plant/CH S | 23224 | kg | Non definito | | | |
| Glass fibre, at plant/RER S | 408 | kg | Non definito | | | |
| Polyvinylchloride (PVC) carbon content (dry matter), use only in PAS2050 v | 198 | kg | Non definito | | | |
| Epoxy resin, liquid, at plant/RER S | 7262 | kg | Non definito | | | |
| Glass wool mat, at plant/CH S | 4358 | kg | Non definito | | | |
| (Inserisci linea qui) | | | | | | |

| Processi | Quantità fisica | Unità di misura | Distribuzione | SD^2 o 2*SD | Min | Max | Commento |
|---|---|---|---|---|---|---|---|
| (Inserisci linea qui) | | | | | | | |

**Figure 20.** Case 2-thermal coating-glass wool in *SimaPro*.



Nome: case2_ventilatedfacade_rockwool

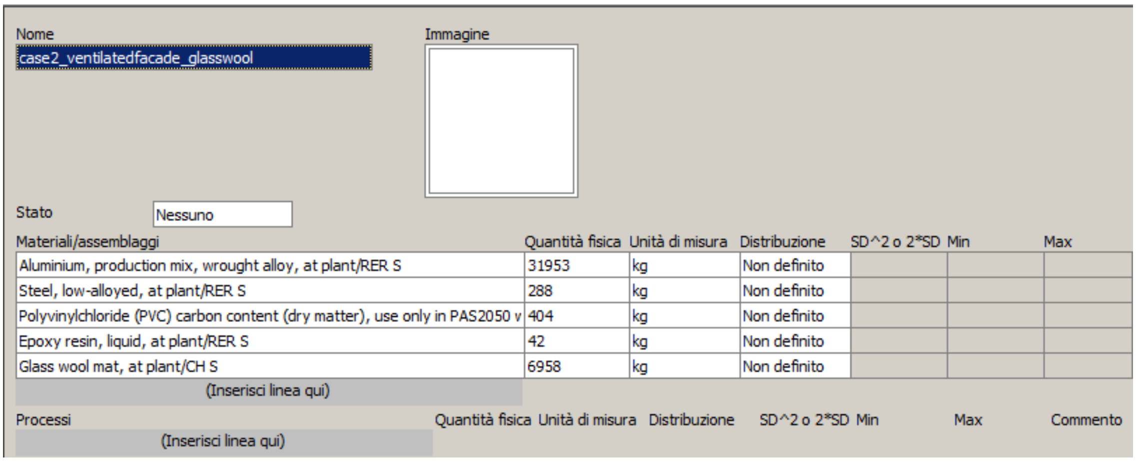
Immagine

Stato: Nessuno

| Materiali/assemblaggi | Quantità fisica | Unità di misura | Distribuzione | SD^2 o 2*SD | Min | Max |
|---|---|---|---|---|---|---|
| Aluminium, production mix, wrought alloy, at plant/RER S | 31953 | kg | Non definito | | | |
| Steel, low-alloyed, at plant/RER S | 288 | kg | Non definito | | | |
| Polyvinylchloride (PVC) carbon content (dry matter), use only in PAS2050 v | 404 | kg | Non definito | | | |
| Epoxy resin, liquid, at plant/RER S | 42 | kg | Non definito | | | |
| Glass wool mat, at plant/CH S | 6958 | kg | Non definito | | | |
| (Inserisci linea qui) | | | | | | |

| Processi | Quantità fisica | Unità di misura | Distribuzione | SD^2 o 2*SD | Min | Max | Commento |
|---|---|---|---|---|---|---|---|
| (Inserisci linea qui) | | | | | | | |

**Figure 21.** Case 2-ventilated façade-rock wool in *SimaPro*.



Nome

case2_ventilatedfacade_glasswool

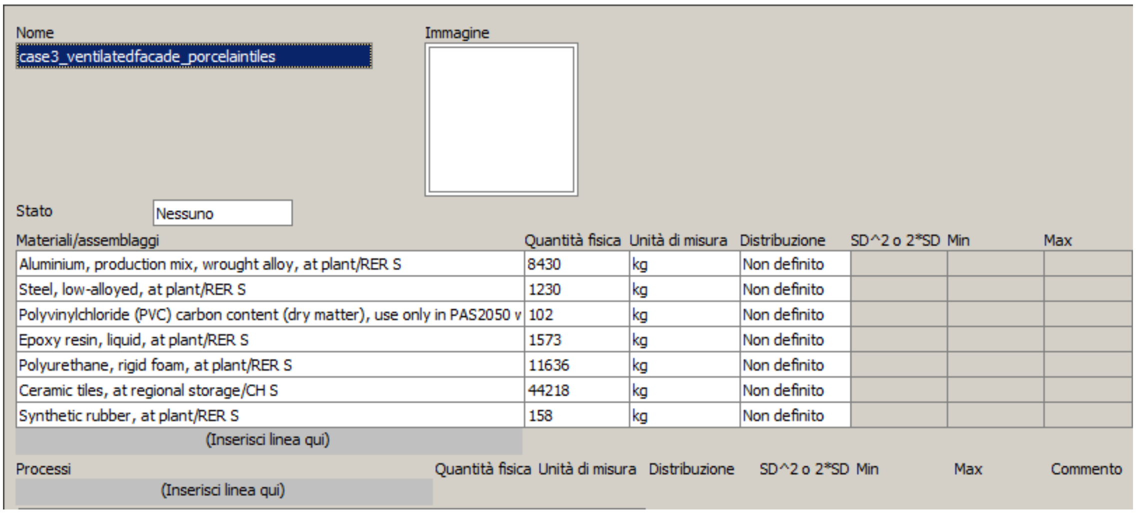
Immagine

Stato: Nessuno

| Materiali/assemblaggi | Quantità fisica | Unità di misura | Distribuzione | SD^2 o 2*SD | Min | Max |
|---|---|---|---|---|---|---|
| Aluminium, production mix, wrought alloy, at plant/RER S | 31953 | kg | Non definito | | | |
| Steel, low-alloyed, at plant/RER S | 288 | kg | Non definito | | | |
| Polyvinylchloride (PVC) carbon content (dry matter), use only in PAS2050 v | 404 | kg | Non definito | | | |
| Epoxy resin, liquid, at plant/RER S | 42 | kg | Non definito | | | |
| Glass wool mat, at plant/CH S | 6958 | kg | Non definito | | | |
| (Inserisci linea qui) | | | | | | |

| Processi | Quantità fisica | Unità di misura | Distribuzione | SD^2 o 2*SD | Min | Max | Commento |
|---|---|---|---|---|---|---|---|
| (Inserisci linea qui) | | | | | | | |

**Figure 22.** Case 2-ventilated façade-glass wool in *SimaPro*.



Nome

case3_ventilatedfacade_porcelaintiles

Immagine

Stato: Nessuno

| Materiali/assemblaggi | Quantità fisica | Unità di misura | Distribuzione | SD^2 o 2*SD | Min | Max |
|---|---|---|---|---|---|---|
| Aluminium, production mix, wrought alloy, at plant/RER S | 8430 | kg | Non definito | | | |
| Steel, low-alloyed, at plant/RER S | 1230 | kg | Non definito | | | |
| Polyvinylchloride (PVC) carbon content (dry matter), use only in PAS2050 v | 102 | kg | Non definito | | | |
| Epoxy resin, liquid, at plant/RER S | 1573 | kg | Non definito | | | |
| Polyurethane, rigid foam, at plant/RER S | 11636 | kg | Non definito | | | |
| Ceramic tiles, at regional storage/CH S | 44218 | kg | Non definito | | | |
| Synthetic rubber, at plant/RER S | 158 | kg | Non definito | | | |
| (Inserisci linea qui) | | | | | | |

| Processi | Quantità fisica | Unità di misura | Distribuzione | SD^2 o 2*SD | Min | Max | Commento |
|---|---|---|---|---|---|---|---|
| (Inserisci linea qui) | | | | | | | |

**Figure 23.** Case 3-ventilated façade-porcelain tiles in *SimaPro*.

The analyse is performed by using *EPD (2008)* method which provides a set of indicators related to different impact categories describing the environmental performance of the products. This method is applied to the different construction and building materials considered as possible solutions to the redevelopment of the hospital of San Benedetto del Tronto. The graphs below (Figures 24 from to 31) show the results for each study case.

### 2.2.1 CASE 1-THERMAL COATING-POLYURETHANE (insulation)

The chart (Figure 24) indicates resin as the most responsible for environmental pollution, because it plays the major role in five out of six impact categories such global warming, photochemical oxidation, acidification, euthrophication and non-renewable depletion.

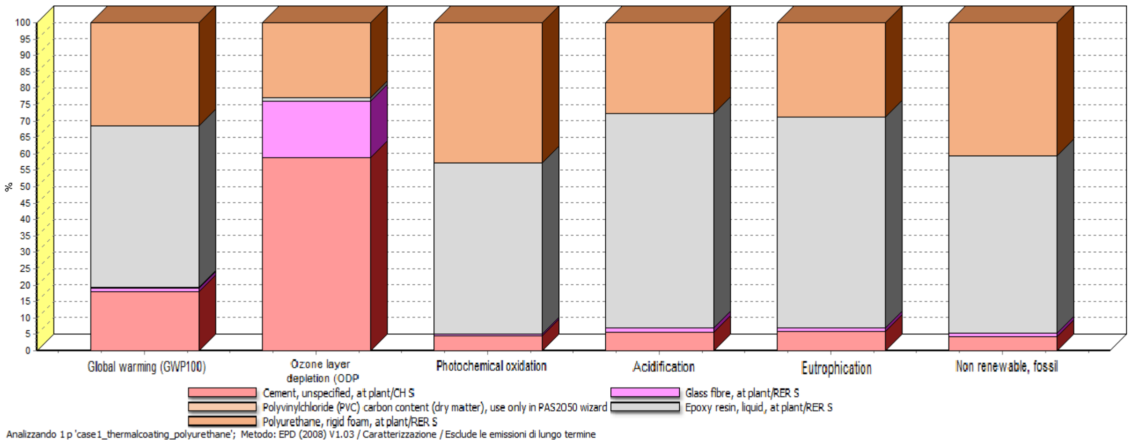



**Figure 24.** Impact categories case 1-thermal coating-polyurethane.

### 2.2.2 CASE 1-VENTILATED FAÇADE-POLYURETHANE (insulation)

The graph (Figure 25) shows at a glance that aluminium alloy reaches the highest percentages for each environmental impact indicators.

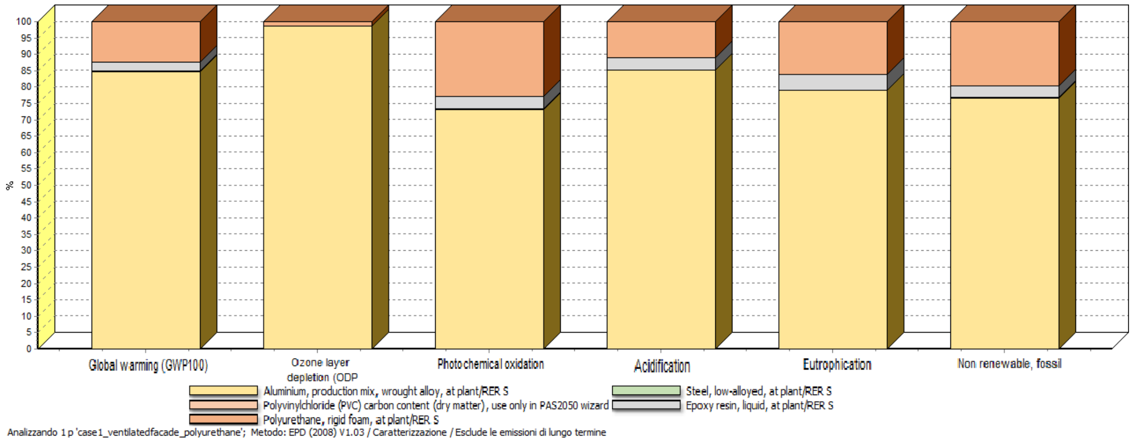



**Figure 25.** Impact categories case 1-ventilated façade-polyurethane.

### 2.2.3 CASE 2-THERMAL COATING-ROCK WOOL (insulation)

The visual representation below (Figure 26) designs resin as the most important material from the environmental point of view, except for the second category; infact, rock wool has got the highest ozone depletion potential.

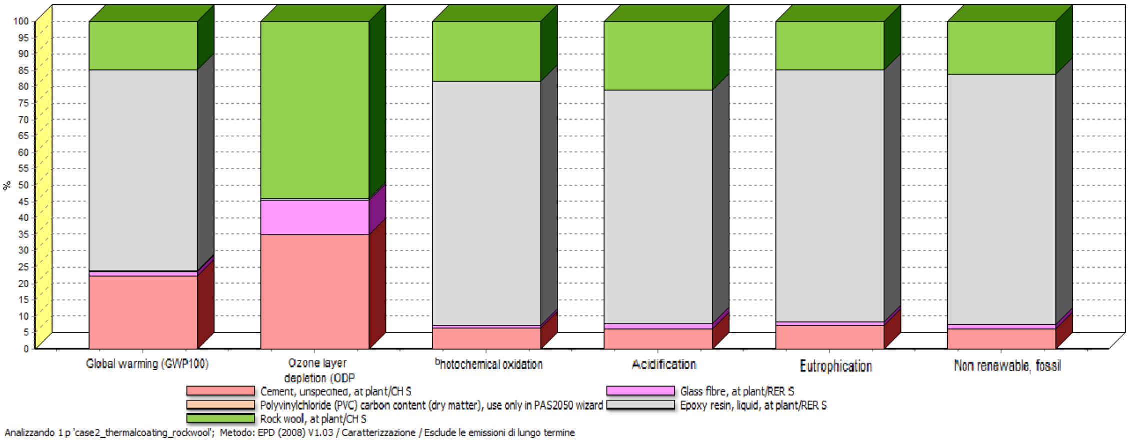



**Figure 26.** Impact categories case 2-thermal coating-rock wool.

### 2.2.4 CASE 2-THERMAL COATING-GLASS WOOL (insulation)

The results provided by this chart (Figure 27) are like the previous ones because glass wool has got the highest ozone depletion potential while resin has got the biggest impact in all the other categories.

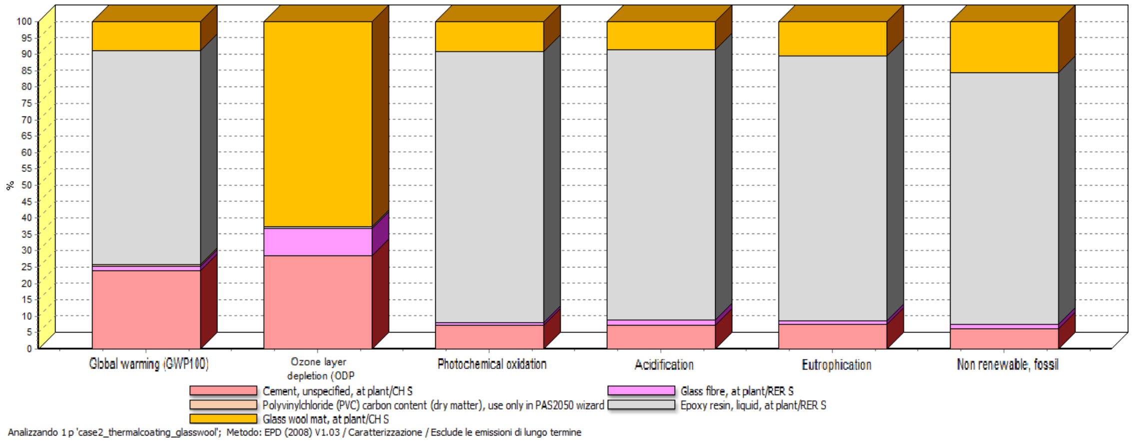



**Figure 27.** Impact categories case 2-thermal coating-glass wool.

### 2.2.5 CASE 2-VENTILATED FAÇADE-ROCK WOOL (insulation)

As outlined by the diagram above (Figure 28), aluminium alloy approximately represents the 90% of the impact in each category, only followed by rock wool.

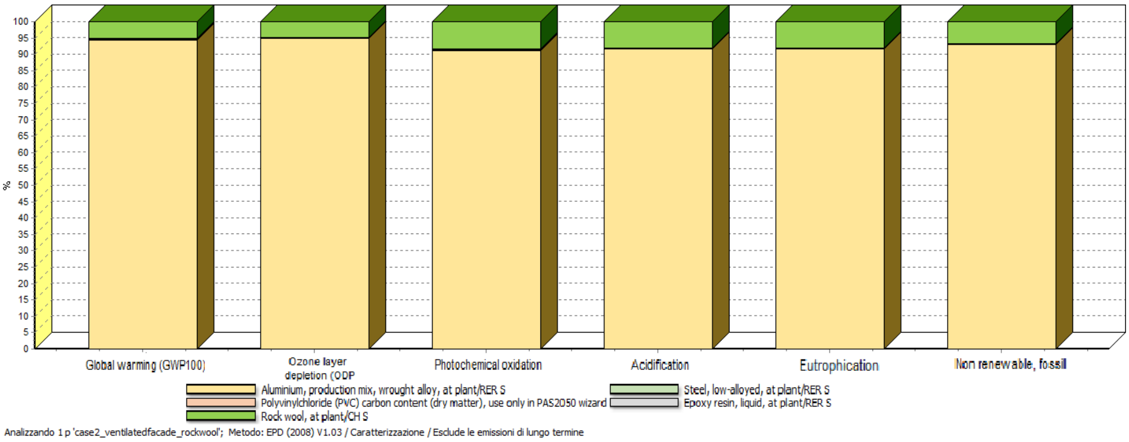



**Figure 28.** Impact categories case 2-ventilated façade-rock wool.

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### 2.2.6 CASE 2-VENTILATED FAÇADE-GLASS WOOL (insulation)

This outline results (Figure 29) are the same to the previous ones; in fact aluminum alloy has got the most elevated impact in each class, followed by the insulating material.

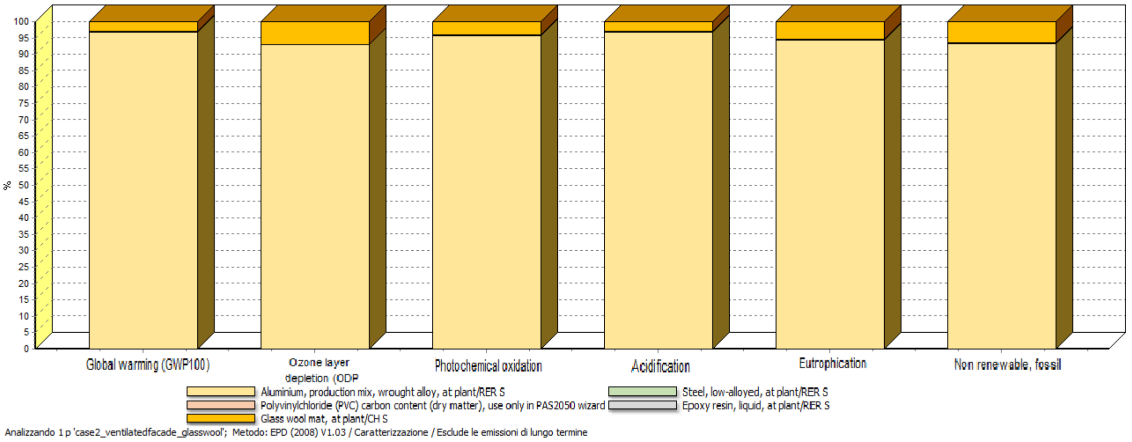


**Figure 29.** Impact categories case 2-ventilated façade-glass wool.

### 2.2.7 CASE 3-VENTILATED FAÇADE-PORCELAIN TILES (cladding)

The results shown by the graph above (Figure 30) are the most diversified. Aluminum alloy represents the most impactful material for three classes, such global warming, acidification and eutrophication and reaches a potential slightly higher than polyurethane in the non-renewable depletion category. Ceramic has the biggest ozone depletion potential, while polyurethane is first material in photochemical oxidation  potential.

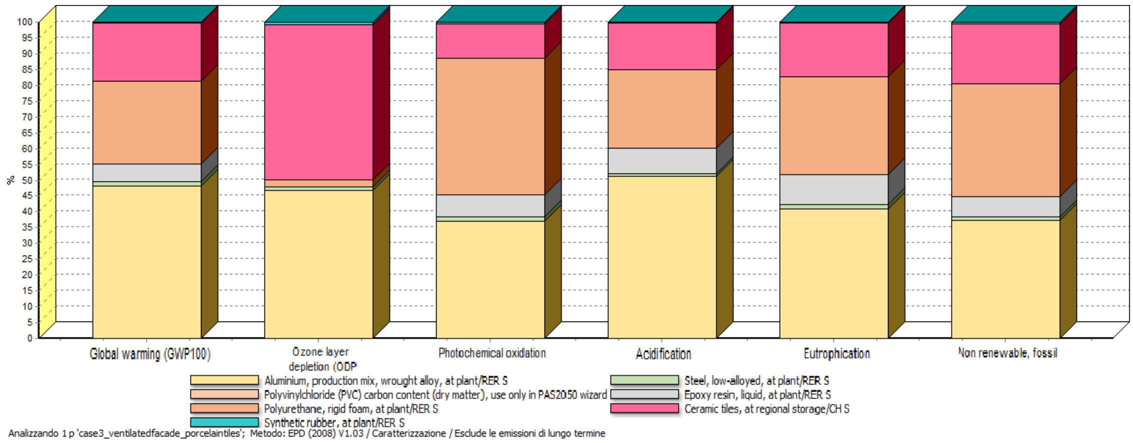


**Figure 30.** Impact categories case 3-ventilated façade-porcelain tiles.

### 2.2.8 COMPARATIVE ANALYSIS OF THE ENVIRONMENTAL IMPACT RESULTS FOR THERMAL COATINGS AND VENTILATED FAÇADES

As can be seen from the graph above (Figure 31), the different building redevelopments considered contribute in the same order to photochemical oxidation, acidification and eutrophication categories; from the most impactful to the least as follow: case 1-ventilated façade-polyurethane, case 2-ventilated façade-rock wool, case 2-ventilated façade-glass wool, case 2-ventilated façade-porcelain tiles, case 1-thermal coating- polyurethane, case 1-thermal coating-rock wool and case 1-thermal coating-glass wool. As for global warming, ozone depletion and non-renewable depletion, while thermal coatings with all kind of insulation materials have the lowest potentials, ventilated façades with porcelain cladding shows intermediate potentials between the other ventilated façades and thermal coatings. Glass wool as insulation in thermal coating seems to be the most sustainable building upgrading: case 2-thermal coating-glass wool has the lowest impact potentials on the environment, exception for ozone depletion category.

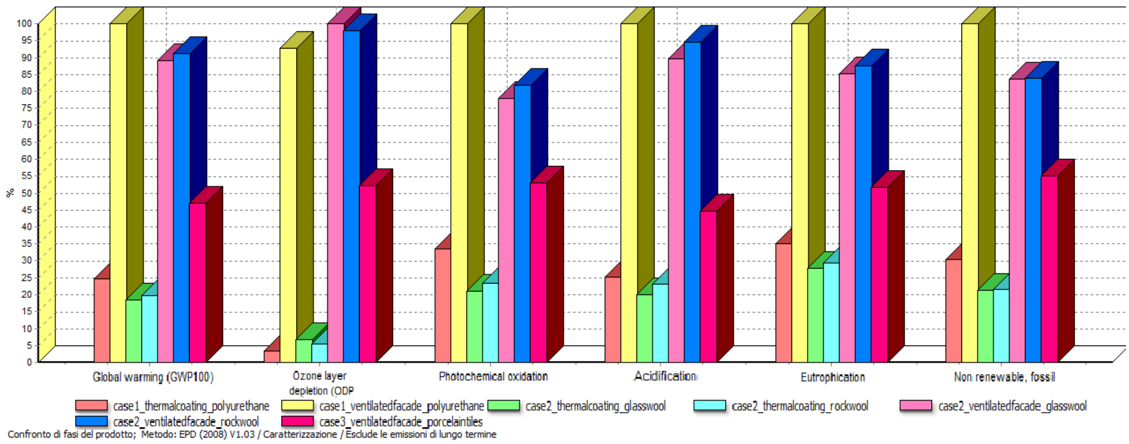


**Figure 31.** Comparative analysis of the environmental impact results for thermal coatings and ventilated façades.

# 3. ENVIRONMENTAL IMPACT RELATED TO THE ENERGY MANAGEMENT OF A SEMPLIFIED BUILDING

In this chapter, the energy management of a building is discussed by using:

- Software: *Edilclima EC700*
- Regulations: *UNI 11300*

The aim is to calculate the amount of $CO_2$ related to the energy consume for the heating management for each case previously mentioned (polyurethane, rock wool or glass wool thermal coats and ventilated façades with different kind of insulation and cladding). Given the structure complexity of the hospital of San Benedetto Del Tronto, a simpler and realistic building is considered in this section. The building analysed is based on an existing masonry building located in Bologna with four floors and as many apartments. The apartment floor plan is showed in Figure 32 and the 3D model of the condominium is represented in Figure 33.

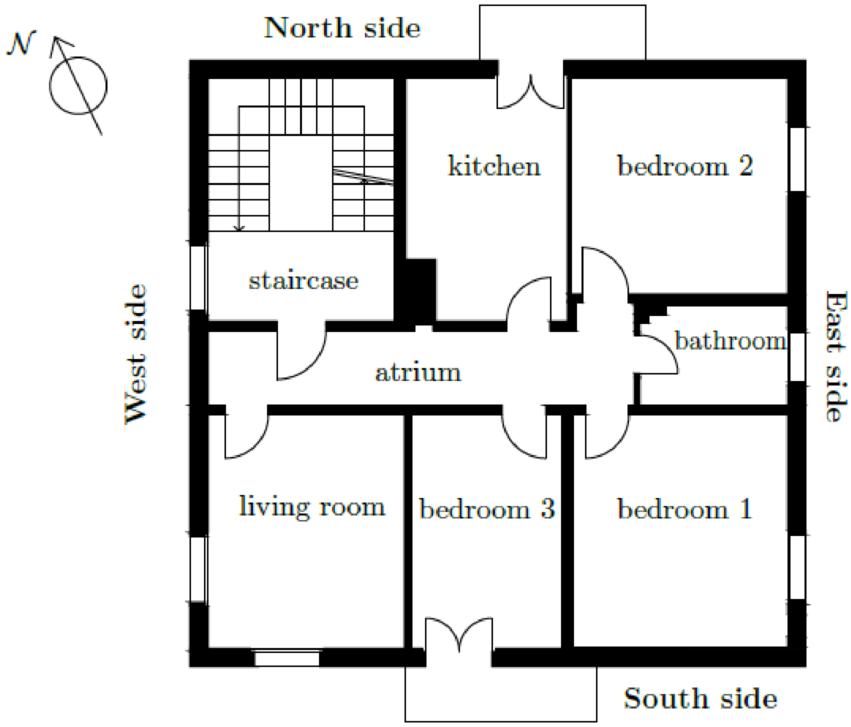


**Figure 32.** Apartment floor plan of the masonry building located in Bologna.

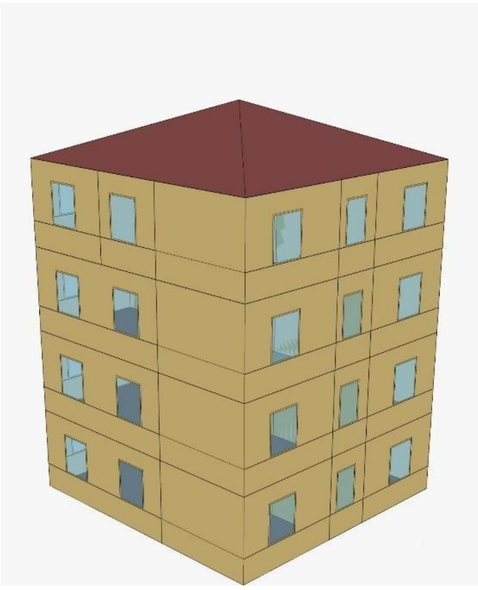

**Figure 33.** 3D Models used to simulate the behavior of the traditional coating insulation (left) and ventilated facades (right) applied on the four sides of the construction. Balconies, which would have only provided shading, have been removed from both the models for the sake of simplicity.

The following tables (Tables 42 from to 55) describe the walls' stratigraphy:

exterior wall (case1_thermalcoating_polyurethane),

exterior wall (case1_ventilatedfaçade_polyurethane),

exterior wall (case2_thermalcoating_rockwool),

exterior wall (case2_thermalcoating_glasswool),

exterior wall (case2_ventilatedfaçade_rockwool),

exterior wall (case2_ventilatedfaçade_glasswool),

exterior wall (case3_ventilatedfaçade_porcelaintiles), interior wall, stair compartment divider, interior floor, ground floor, ceiling (top floor), interior ceiling, exterior roof.

| Legend | | |
|---|---|---|
| s | depth | mm |
| Cond. | thermal conductivity | W/(mK) |
| R | thermal resistance | $(m^2K)/W$ |
| M.V. | density | $kg/m^3$ |
| C.T. | specific heat capacity | kJ/(kgK) |
| R.V. | resistance to vapor diffusion | - |

| N. | Description | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal surface resistant | - | - | 0,130 | - | - | - |
| 1 | Cement and sand plaster | 10,00 | 1,000 | 0,010 | 1800 | 1,00 | 10 |
| 2 | Brick masonry external walls (um. 1.5%) | 280,00 | 0,810 | 0,346 | 1800 | 1,00 | 7 |
| 3 | Klebocem | 4,00 | 0,470 | 0,009 | 1200 | 1,00 | 80 |
| 4 | Rigid gas permeable polyurethane (80 mm < d <= 120 mm) | 90,00 | 0,026 | 3,462 | 35 | 1,40 | 60 |
| 5 | Klebocem | 4,00 | 0,470 | 0,009 | 1200 | 1,00 | 80 |
| - | External surface resistant | - | - | 0,060 | - | - | - |

**Table 42.** Stratigraphy case 1_thermal coating_polyurethane.

| N. | Description | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal surface resistant | - | - | 0,130 | - | - | - |
| 1 | Cement and sand plaster | 10,00 | 1,000 | - | 1800 | 1,00 | 10 |
| 2 | Brick masonry external walls (um. 1.5%) | 280,00 | 0,810 | - | 1800 | 1,00 | 7 |
| 3 | Rigid gas permeable polyurethane (80 mm < d <= 120 mm) | 140,00 | 0,026 | - | 35 | 1,40 | 60 |
| 4 | Weakly ventilated interspace Av = 600 mm² / m | 60,00 | - | - | - | - | - |
| 5 | Aluminium | 0,40 | 220,000 | - | 2700 | 0,88 | - |
| - | External surface resistant | - | - | 0,060 | - | - | - |

**Table 43.** Stratigraphy case 1_ventilated façade_polyurethane.

| N. | Description | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal surface resistant | - | - | 0,130 | - | - | - |
| 1 | Cement and sand plaster | 10,00 | 1,000 | 0,010 | 1800 | 1,00 | 10 |
| 2 | Brick masonry external walls (um. 1.5%) | 280,00 | 0,810 | 0,346 | 1800 | 1,00 | 7 |
| 3 | Klebocem | 4,00 | 0,470 | 0,009 | 1200 | 1,00 | 80 |
| 4 | Rock wool panel | 116,00 | 0,035 | 3,314 | 40 | 1,03 | 1 |
| 5 | Klebocem | 4,00 | 0,470 | 0,009 | 1200 | 1,00 | 80 |
| - | External surface resistant | - | - | 0,060 | - | - | - |

**Table 44.** Stratigraphy case 2_thermal coating_rock wool.

| N. | Description | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal surface resistant | - | - | 0,130 | - | - | - |
| 1 | Cement and sand plaster | 10,00 | 1,000 | 0,010 | 1800 | 1,00 | 10 |
| 2 | Brick masonry external walls (um. 1.5%) | 280,00 | 0,810 | 0,346 | 1800 | 1,00 | 7 |
| 3 | Klebocem | 4,00 | 0,470 | 0,009 | 1200 | 1,00 | 80 |
| 4 | Glass wool panel | 116,00 | 0,034 | 3,412 | 25 | 1,03 | 1 |
| 5 | Klebocem | 4,00 | 0,470 | 0,009 | 1200 | 1,00 | 80 |
| - | External surface resistant | - | - | 0,060 | - | - | - |

**Table 45.** Stratigraphy case 2_thermal coating_glass wool.

| N. | Description | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal surface resistance | - | - | *0,130* | - | - | - |
| 1 | Cement and sand plaster | *10,00* | *1,000* | - | *1800* | *1,00* | *10* |
| 2 | Brick masonry external walls (um. 1.5%) | *280,00* | *0,810* | - | *1800* | *1,00* | *7* |
| 3 | Rock wool panel | *183,00* | *0,035* | - | *40* | *1,03* | *1* |
| 4 | Weakly ventilated interspace Av = 600 mm² / m | *60,00* | - | - | - | - | - |
| 5 | Aluminium | *0,40* | *220,000* | - | *2700* | *0,88* | - |
| - | External surface resistance | - | - | *0,060* | - | - | - |

**Table 46.** Stratigraphy case 2_ventilated façade_rock wool.

| N. | Description | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal surface resistance | - | - | *0,130* | - | - | - |
| 1 | Cement and sand plaster | *10,00* | *1,000* | - | *1800* | *1,00* | *10* |
| 2 | Brick masonry external walls (um. 1.5%) | *280,00* | *0,810* | - | *1800* | *1,00* | *7* |
| 3 | Glass wool panel | *183,00* | *0,034* | - | *25* | *1,03* | *1* |
| 4 | Weakly ventilated interspace Av = 600 mm² / m | *60,00* | - | - | - | - | - |
| 5 | Aluminium | *0,40* | *220,000* | - | *2700* | *0,88* | - |
| - | External surface resistance | - | - | *0,060* | - | - | - |

**Table 47.** Stratigraphy case 2_ventilated façade_glass wool.

| N. | Description | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal surface resistant | - | - | *0,130* | - | - | - |
| 1 | Cement and sand plaster | *10,00* | *1,000* | *0,010* | *1800* | *1,00* | *10* |
| 2 | Brick masonry external walls (um. 1.5%) | *280,00* | *0,810* | *0,346* | *1800* | *1,00* | *7* |
| 3 | Rigid gas permeable polyurethane (80 mm < d <= 120 mm) | *140,00* | *0,026* | *5,385* | *35* | *1,40* | *60* |
| 4 | Strongly ventilated interspace Av> 1500 mm² / m | *60,00* | - | - | - | - | - |
| 5 | Porcelain_tiles | *0,70* | *1,460* | - | *2300* | *0,77* | - |
| - | External surface resistant | - | - | *0,060* | - | - | - |

**Table 48.** Stratigraphy case3_ventilated façade_porcelain tiles.

| N. | Description | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal surface resistance | - | - | *0,130* | - | - | - |
| 1 | Lime and plaster plaster | *10,00* | *0,700* | *0,014* | *1400* | *1,00* | *10* |
| 2 | Perforated brick | *100,00* | *0,370* | *0,270* | *780* | *0,84* | *9* |
| 3 | Lime and plaster plaster | *10,00* | *0,700* | *0,014* | *1400* | *1,00* | *10* |
| - | External surface resistance | - | - | *0,130* | - | - | - |

**Table 49.** Interior wall.

| N. | Description | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal surface resistance | - | - | *0,130* | - | - | - |
| 1 | Lime and plaster plaster | *10,00* | *0,700* | *0,014* | *1400* | *1,00* | *10* |
| 2 | Half-full block | *200,00* | *0,426* | *0,469* | *820* | *0,84* | *7* |
| 3 | Lime and plaster plaster | *10,00* | *0,700* | *0,014* | *1400* | *1,00* | *10* |
| - | External surface resistance | - | - | *0,130* | - | - | - |

**Table 50.** Stair compartment divider.

| N. | Description | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal surface resistance | - | - | *0,170* | - | - | - |
| 1 | Ceramic tiles (tiles) | *10,00* | *1,300* | *0,008* | *2300* | *0,84* | *9999999* |
| 2 | Concrete distribution screed with mesh | *50,00* | *1,490* | *0,034* | *2200* | *0,88* | *70* |
| 3 | Expanded polystyrene synth. (lightening structures) | *30,00* | *0,045* | *0,667* | *15* | *1,45* | *30* |
| 4 | 2-3 Light pre-dosed substrate | *70,00* | *0,170* | *0,412* | *650* | *1,00* | *6* |
| 5 | Concrete with medium density | *40,00* | *1,350* | *0,030* | *2000* | *1,00* | *100* |
| 6 | Floor block | *260,00* | *0,667* | *0,390* | *842* | *0,84* | *9* |
| - | External surface resistance | - | - | *0,170* | - | - | - |

**Table 51.** Interior floor.

| N. | Description | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal surface resistance | - | - | *0,170* | - | - | - |
| 1 | Ceramic tiles (tiles) | *10,00* | *1,300* | *0,008* | *2300* | *0,84* | *9999999* |
| 2 | Concrete distribution screed with mesh | *50,00* | *1,490* | *0,034* | *2200* | *0,88* | *70* |
| 3 | Expanded polystyrene synth. (lightening structures) | *30,00* | *0,045* | *0,667* | *15* | *1,45* | *30* |
| 4 | 2-3 Light pre-dosed substrate | *70,00* | *0,170* | *0,412* | *650* | *1,00* | *6* |
| 5 | Concrete with medium density | *60,00* | *1,350* | *0,044* | *2000* | *1,00* | *100* |
| 6 | Non-ventilated interspace Av <500 mm² / m | *300,00* | *1,304* | *0,230* | - | - | - |
| 7 | Coarse gravel without clay (um. 5%) | *300,00* | *1,200* | *0,250* | *1700* | *1,00* | *5* |
| - | External surface resistance | - | - | *0,040* | - | - | - |

**Table 52.** Ground floor

| N. | Description | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | External surface resistance | - | - | *0,100* | - | - | - |
| 1 | Ceramic tiles (tiles) | *10,00* | *1,300* | *0,008* | *2300* | *0,84* | *9999999* |
| 2 | Concrete distribution screed with mesh | *50,00* | *1,490* | *0,034* | *2200* | *0,88* | *70* |
| 3 | Expanded polystyrene synth. (lightening structures) | *30,00* | *0,045* | *0,667* | *15* | *1,45* | *30* |
| 4 | 2-3 Light pre-dosed substrate | *70,00* | *0,170* | *0,412* | *650* | *1,00* | *6* |
| 5 | Concrete with medium density | *40,00* | *1,350* | *0,030* | *2000* | *1,00* | *100* |
| 6 | Floor block | *260,00* | *0,667* | *0,390* | *842* | *0,84* | *9* |
| - | Internal surface resistance | - | - | *0,100* | - | - | - |

**Table 53.** Ceiling (top floor).

| N. | Description | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | External surface resistance | - | - | *0,100* | - | - | - |
| 1 | Ceramic tiles (tiles) | *10,00* | *1,300* | *0,008* | *2300* | *0,84* | *9999999* |
| 2 | Concrete distribution screed with mesh | *50,00* | *1,490* | *0,034* | *2200* | *0,88* | *70* |
| 3 | Expanded polystyrene synth. (lightening structures) | *30,00* | *0,045* | *0,667* | *15* | *1,45* | *30* |
| 4 | 2-3 Light pre-dosed substrate | *70,00* | *0,170* | *0,412* | *650* | *1,00* | *6* |
| 5 | concrete with medium density | *40,00* | *1,350* | *0,030* | *2000* | *1,00* | *100* |
| 6 | Floor block | *260,00* | *0,667* | *0,390* | *842* | *0,84* | *9* |
| - | External surface resistance | - | - | *0,100* | - | - | - |

**Table 54.** Interior ceiling

| N. | Description | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | External surface resistance | - | - | *0,060* | - | - | - |
| 1 | Ceramic tiles (tiles) | *10,00* | *1,300* | *0,008* | *2300* | *0,84* | *9999999* |
| 2 | Concrete distribution screed with mesh | *20,00* | *1,490* | *0,013* | *2200* | *0,88* | *70* |
| 3 | Expanded polystyrene synth. (lightening structures) | *100,00* | *0,045* | *2,222* | *15* | *1,45* | *30* |
| 4 | Concrete with medium density | *40,00* | *1,350* | *0,030* | *2000* | *1,00* | *100* |
| 5 | Floor block | *260,00* | *0,667* | *0,390* | *842* | *0,84* | *9* |
| - | Internal surface resistance | - | - | *0,100* | - | - | - |

**Table 55.** Exterior Roof.

As already described, the building analysed is a condominium of four apartments with independent heating; Table 56 summarizes the details of the heating system with no production of domestic water. The production of domestic water is not considered because its energy requirement is not directly connected to the building envelope and insulation material.

| Realistic and simplified building | | |
|---|---|---|
| Heating system | | |
| Condensing boiler | Generation efficiency | 107,10% |
| Radiant floor | Emission efficiency | 98,0% |
| Insulated pipes | Distribution efficiency | 98,1% |
| Environmental + climatic regulation | Regulation efficiency | 97,0% |
| | Total useful efficiency | 99,9% |

**Table 56.** Details of the heating system in the realistic and simplified building.

The thermal transmittance U [W/(m$^2$ K)] is the rate of transfer of heat through matter; the higher is the wall transmittance, the more heat is dispersed outside. The transmittance values goes from 0,164 W/(m$^2$ K) (ventilated façade with polyurethane or glass wool as insulation materials) to 0,259 W/(m$^2$ K) (rock wool thermal coat) and the power dispersed swings between the 15,2% and the 22,8% (Table 57).

| | Winter power | | |
|---|---|---|---|
| | Dispersions of external walls | | |
| | U [W/(m$^2$ K)] | Qtr [W] | % |
| case1_thermalcoating_polyurethane | 0,250 | 3050 | 21,5 |
| case1_ventilatedfaçade_polyurethane | 0,164 | 1890 | 15,2 |
| case2_thermalcoating_rockwool | 0,259 | 2980 | 22,8 |
| case2_thermalcoating_glasswool | 0,253 | 2900 | 22,3 |
| case2_ventilatedfaçade_rockwool | 0,169 | 1940 | 15,5 |
| case2_ventilatedfaçade_glasswool | 0,164 | 1887 | 15,2 |
| case3_ventilatedfaçade_porcelaintiles | 0,167 | 1915 | 15,4 |

**Table 57.** Dispersion of external walls.

As for the energy requirements for air conditioning Qc,nd expressed in kwh, thermal coating with polyurethane as insulation (case 1) requires the less energy (Table 58 and Figure 34).

| | | Summer energy | | | |
|---|---|---|---|---|---|
| | | Energy requirements air conditioning | | | |
| | | Qc,nd [kWh] | | | |
| | | June | July | August | sum |
| 1 | case1_thermalcoating_polyurethane | 2617 | 4386 | 2427 | 9430 |
| 2 | case1_ventilatedfaçade_polyurethane | 2667 | 4284 | 2511 | 9462 |
| 3 | case2_thermalcoating_rockwool | 2732 | 4417 | 2565 | 9714 |
| 4 | case2_thermalcoating_glasswool | 2733 | 4414 | 2567 | 9714 |
| 5 | case2_ventilatedfaçade_rockwool | 2660 | 4278 | 2504 | 9442 |
| 6 | case2_ventilatedfaçade_glasswool | 2663 | 4278 | 2508 | 9449 |
| 7 | case3_ventilatedfaçade_porcelaintiles | 2630 | 4242 | 2473 | 9345 |

**Table 58.** Energy requirements for air conditioning in June, July and August.

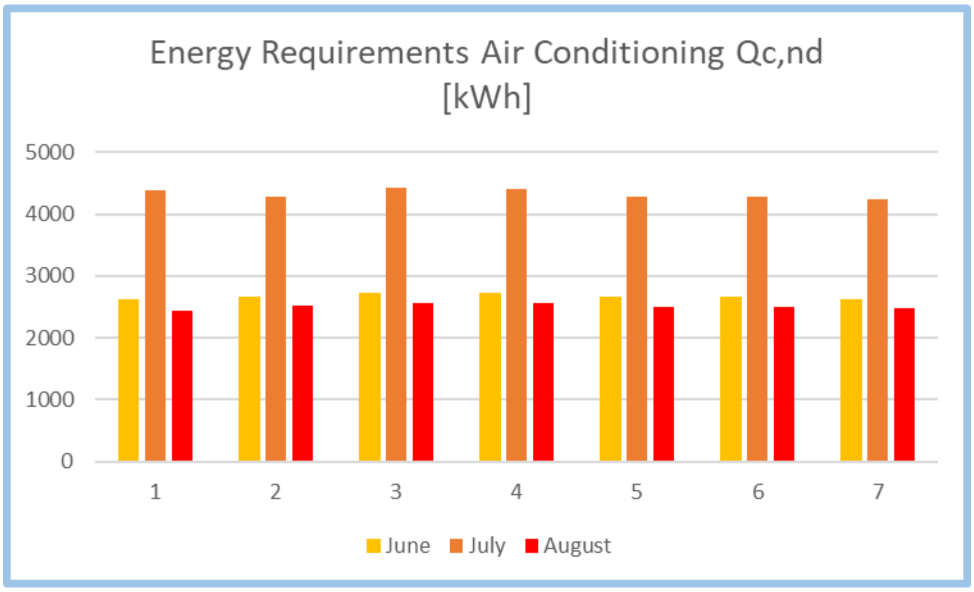


**Figure 34.** Energy requirements for air conditioning in June, July and August. Legend contained in the table above.

The Table below (Table 59) is divided into the various construction technologies and shows the data related to the kilograms of carbon dioxide produced by the management of the heating system during the wintertime [kg $CO_2/(m^2$ year)]. This amount of $CO_2$ is multiplied by the steppable surface of the entire building (333,77 $m^2$) and then by 10 and 25 years, which are the useful lives of thermal coats and ventilated façades respectively. Results are stable around the same values and are graphed in Figure 35.

| | | Edilclima | | | | | |
|---|---|---|---|---|---|---|---|
| | | Energy consumption heating system | | | | | |
| | | [kg CO2/(m2 year)] | # years | # years | [m2] | [kg CO2] 10 years | [kg CO2] 25 years |
| 1 | case1_thermalcoating_polyurethane | 46 | 10 | 25 | 333,77 | 153534,2 | 383835,5 |
| 2 | case1_ventilatedfaçade_polyurethane | 39 | 10 | 25 | 333,77 | 130170,3 | 325425,8 |
| 3 | case2_thermalcoating_rockwool | 41 | 10 | 25 | 333,77 | 136845,7 | 342114,3 |
| 4 | case2_thermalcoating_glasswool | 41 | 10 | 25 | 333,77 | 136845,7 | 342114,3 |
| 5 | case2_ventilatedfaçade_rockwool | 43 | 10 | 25 | 333,77 | 143521,1 | 358802,8 |
| 6 | case2_ventilatedfaçade_glasswool | 39 | 10 | 25 | 333,77 | 130170,3 | 325425,8 |
| 7 | case3_ventilatedfaçade_porcelaintiles | 40 | 10 | 25 | 333,77 | 133508 | 333770,0 |

**Table 59.** Energy consumption heating system.

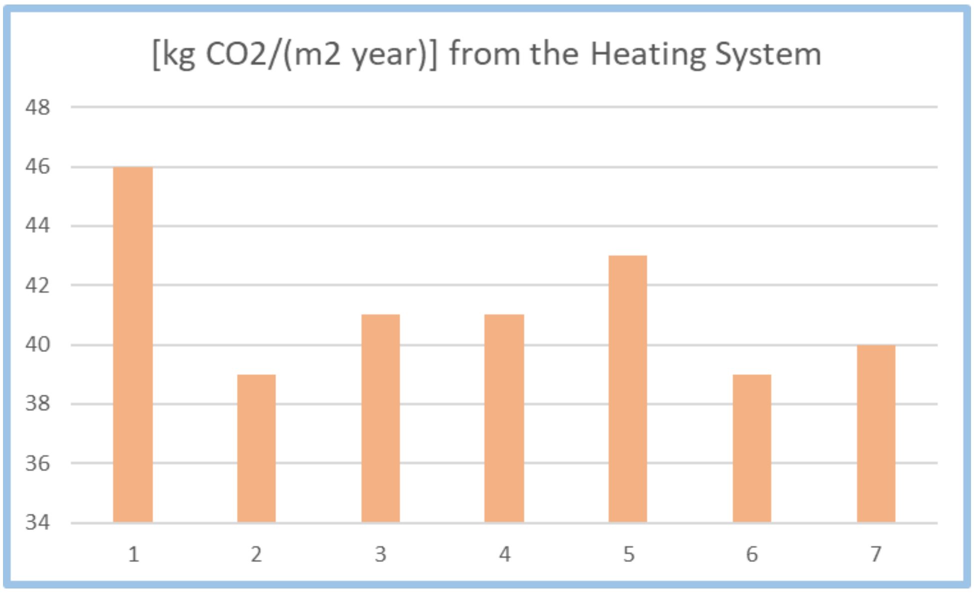


**Figure 35.** Energy consumption heating system [kg $CO_2/(m^2$ year)]. Legend contained in the table above.

# 4. COMPARISON OF THE ENVIRONMENTAL IMPACT RESULTS AND DISCUSSION

The aim of chapter 4 is crossing the results from the previous sections. Chapter 2 provides the kilograms of $CO_2$ equivalent per $m^2$ (*global warming* impact category) derived from the production of the different building technologies for the requalification of the envelope of "*Madonna Del Soccorso*" hospital (Ascoli Piceno). These values are then multiplied by the $m^2$ of the external wall surface (411,36 $m^2$, Table 60) of the realistic and simplified building considered in Chapter 3 (Table 61 and Figure 36). Chapter 3 contains the calculations related to kilograms of $CO_2$ per ($m^2$ year) derived from the energy consumed by managing the heating system of the realistic and simplified building. These amounts of $CO_2$ are then multiplied by the steppable surface (333,77 $m^2$, Table 60) and the useful lives of thermal coating (10 years) and ventilated façade (25 years) respectively (Table 63 and Figure 37). In summing up all the results, ventilated façades have the highest impact on the environment in the production stage (Figure 36) and polyurethane thermal coat requires the most energy for the heating during the wintertime (Figure 37).

| Realistic and simplified building | | |
|---|---|---|
| surface of building envelope | [$m^2$] | 411,36 |
| steppable surface | [$m^2$] | 333,77 |

**Table 60.** Surfaces of the realistic and simplified building.

| | | SimaPro | | |
|---|---|---|---|---|
| | | Production | | |
| | | [kg CO2 eq/m$^2$] | [m$^2$] | [kg $CO_2$ eq] |
| 1 | case1_thermalcoating_polyurethane | 43 | 411,36 | 17688,48 |
| 2 | case1_ventilatedfaçade_polyurethane | 175 | 411,36 | 71988 |
| 3 | case2_thermalcoating_rockwool | 35 | 411,36 | 14397,6 |
| 4 | case2_thermalcoating_glasswool | 32 | 411,36 | 13163,52 |
| 5 | case2_ventilatedfaçade_rockwool | 159 | 411,36 | 65406,24 |
| 6 | case2_ventilatedfaçade_glasswool | 156 | 411,36 | 64172,16 |
| 7 | case3_ventilatedfaçade_porcelaintiles | 82 | 411,36 | 33731,52 |

**Table 61.** [kg $CO_2$ eq] from production.

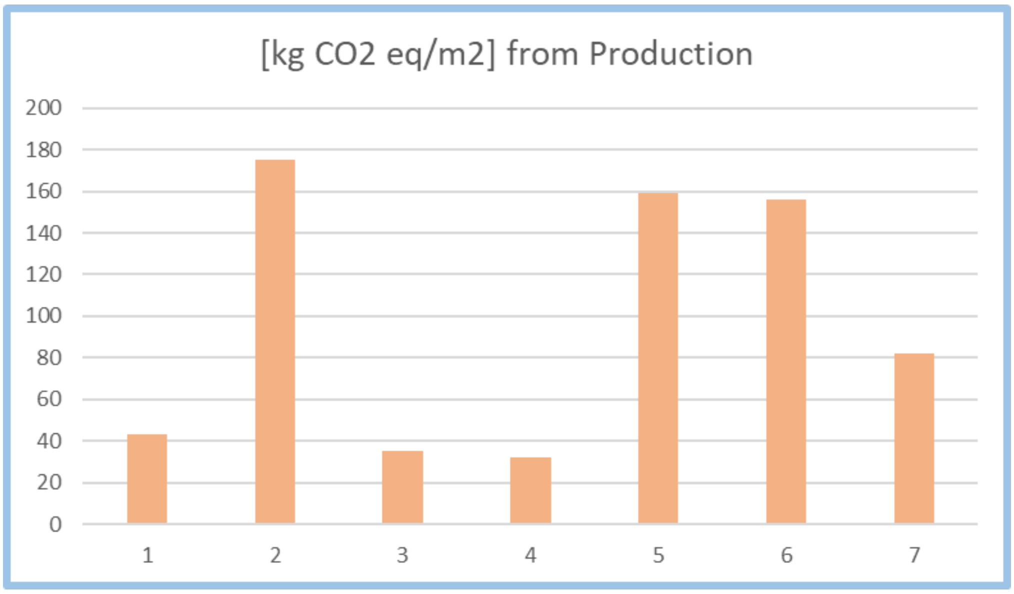


**Figure 36.** [kg $CO_2$ eq] from production. Legend contained in the table above.

| | | Edilclima | | | | | |
|---|---|---|---|---|---|---|---|
| | | Energy consumption heating system | | | | | |
| | | [kg CO2/(m2 year)] | # years | # years | [m2] | [kg CO2] 10 years | [kg CO2] 25 years |
| 1 | case1_thermalcoating_polyurethane | 46 | 10 | 25 | 333,77 | 153534,2 | 383835,5 |
| 2 | case1_ventilatedfaçade_polyurethane | 39 | 10 | 25 | 333,77 | 130170,3 | 325425,8 |
| 3 | case2_thermalcoating_rockwool | 41 | 10 | 25 | 333,77 | 136845,7 | 342114,3 |
| 4 | case2_thermalcoating_glasswool | 41 | 10 | 25 | 333,77 | 136845,7 | 342114,3 |
| 5 | case2_ventilatedfaçade_rockwool | 43 | 10 | 25 | 333,77 | 143521,1 | 358802,8 |
| 6 | case2_ventilatedfaçade_glasswool | 39 | 10 | 25 | 333,77 | 130170,3 | 325425,8 |
| 7 | case3_ventilatedfaçade_porcelaintiles | 40 | 10 | 25 | 333,77 | 133508 | 333770,0 |

**Table 62.** Energy consumption heating system.

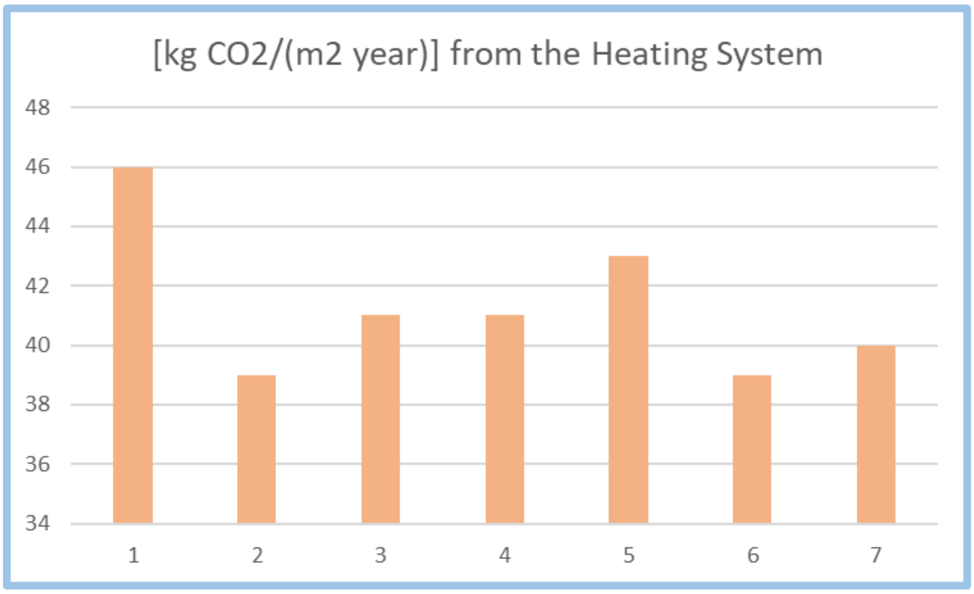


**Figure 37.** Energy consumption heating system. Legend contained in the table above.

The table and the graph below (Table 63 and Figure 38) summarizes all the data related to the kilograms of $CO_2$ derived from both the production and the managing of the heating system. Thermal coating represents the building technology with the lowest environmental impact from the global warming point of view (release of $CO_2$ in the environment). Thinking about the incidence of the kilograms of carbon dioxide from production on the quantity of carbon dioxide from energy consumption (Figure 39), glass wool thermal coat has the lowest percentage during both the shortest and the longest period. The percentages related to ventilated façades decrease significantly from 10 to 25 years: ventilated façades represent an ecological choice in the long run, while thermal coats need to be substituted after about 10 years (Table 64).

| Legend | |
|---|---|
| 1 | case1_thermalcoating_polyurethane |
| 2 | case1_ventilatedfaçade_polyurethane |
| 3 | case2_thermalcoating_rockwool |
| 4 | case2_thermalcoating_glasswool |
| 5 | case2_ventilatedfaçade_rockwool |
| 6 | case2_ventilatedfaçade_glasswool |
| 7 | case3_ventilatedfaçade_porcelaintiles |

| | SimaPro | Edilclima | Edilclima | | | sum | sum |
|---|---|---|---|---|---|---|---|
| | Production | Energy consumption | Energy consumption | | | | |
| | [kg $CO_2$ eq] | [kg $CO_2$] 10 years | [kg $CO_2$] 25 years | 10 years | 25 years | [kg $CO_2$] 10 years | [kg $CO_2$] 25 years |
| 1 | 17688,48 | 153534,2 | 383835,5 | 12% | 5% | 171222,7 | 401524,0 |
| 2 | 71988 | 130170,3 | 325425,8 | 55% | 22% | 202158,3 | 397413,8 |
| 3 | 14397,6 | 136845,7 | 342114,3 | 11% | 4% | 151243,3 | 356511,9 |
| 4 | 13163,52 | 136845,7 | 342114,3 | 10% | 4% | 150009,2 | 355277,8 |
| 5 | 65406,24 | 143521,1 | 358802,8 | 46% | 18% | 208927,3 | 424209,0 |
| 6 | 64172,16 | 130170,3 | 325425,8 | 49% | 20% | 194342,5 | 389597,9 |
| 7 | 33731,52 | 133508,0 | 333770,0 | 25% | 10% | 167239,5 | 367501,5 |

**Table 63.** Summary data related to the quantity of $CO_2$.

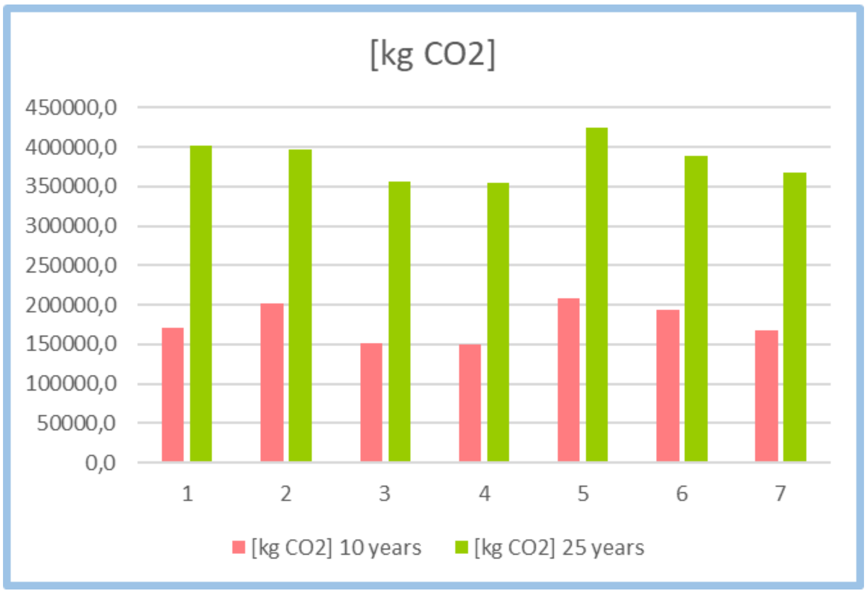


**Figure 38.** Summary data related to the quantity of $CO_2$ for 10 or 25 years. Legend contained in the table above.

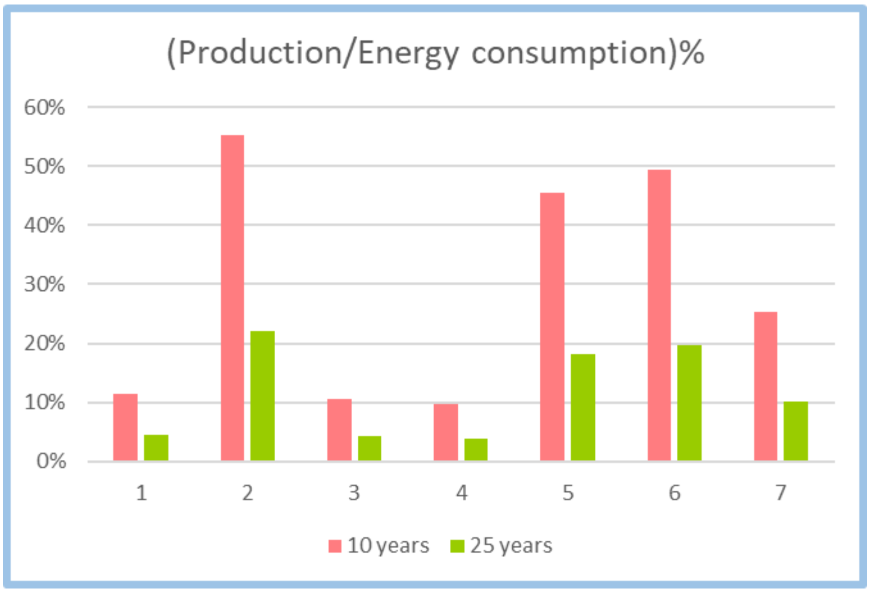


**Figure 39.** (Production/Energy consumption) % for 10 or 25 years. Legend contained in the table above.

| | | 10 years | 25 years | Difference |
|---|---|---|---|---|
| 1 | case1_thermalcoating_polyurethane | 12% | 5% | 7% |
| 2 | case1_ventilatedfaçade_polyurethane | 55% | 22% | 33% |
| 3 | case2_thermalcoating_rockwool | 11% | 4% | 6% |
| 4 | case2_thermalcoating_glasswool | 10% | 4% | 6% |
| 5 | case2_ventilatedfaçade_rockwool | 46% | 18% | 27% |
| 6 | case2_ventilatedfaçade_glasswool | 49% | 20% | 30% |
| 7 | case3_ventilatedfaçade_porcelaintiles | 25% | 10% | 15% |

**Table 64.** Difference between (Production/Energy consumption) % for 10 and 25 years.

Goal and scope of this study was the evaluation of the environmental impact related to the application to an existing building of different envelope redevelopments. While the building taken into consideration was the "*Madonna del Soccorso*" hospital located in San Benedetto del Tronto, the improvements studied were: polyurethane, rock wool and glass wool thermal coats, ventilates façades with polyurethane, rock wool or glass wool insulation and aluminum or ceramic cladding. The analysis was performed using *SimaPro* software and *Ecoinvent* database. The results obtained by *EPD (2008)* method revealed the glass wool thermal coat to be the most sustainable envelope in terms of global warming, photochemical oxidation, acidification, eutrophication and non-renewable potentials. In this case, the resin is the most responsible for the pollution. Among ventilated façades, adopting polyurethane as insulation and porcelain tiles as cladding is the solution with the least environmental impact. In this building envelope, aluminum is the most impactful material in global warming, acidification, eutrophication and non-renewable depletion categories, ceramic has the biggest ozone depletion potential and polyurethane is first material in photochemical oxidation potential. After the EPD analysis, a simplified but realistic building was taken into consideration to estimate the amount of carbon dioxide derived from the managing of the heating system adopting the different kind of envelopes already mentioned. Calculations were made using *Edilclima* software based on *UNI 11300*. Data were extended to both the useful lives of thermal coatings and ventilated façades, 10 and 25 years respectively. The $CO_2$ results of both researches, EPD and managing of the heating system, were added up: glass wool thermal coat resulted to be the most ecological choice. In general, thermal coatings come about to have the lowest $CO_2$ release in the environment. Considering the percentage of the kilograms of carbon dioxide derived from the raw materials on the quantity of carbon dioxide from the energy consumption, ventilated façades had a significant reduction passing from 10 to 25 years: this finds justification in the fact that ventilated façades have a lower environmental footprint in the long run, as they don't need to be replaced after about 10 years like thermal coatings.

# CONCLUSION

The building sector consumes around the 40% of the global energy in the European Union. [1] The constructive sector has a great repercussion in the whole environmental impact of the industrial societies, there is a strong need to provide information about the environmental performance of products and services with objectivity, comparability and credibility, as it is pointed out by Bovea et al. [7] The main instruments that can be used to communicate environmental information, and thereby increasing people awareness, are environmental declarations and eco-labels, based on the ISO 14000 series of standards. One of these eco- labels type III is the *environmental product declaration* (EPD), which provides a set of indicators based on a *life cycle assessment* (LCA) and related to different impact categories describing the environmental performance of the product. These categories are global warming, ozone layer depletion, photochemical oxidation, acidification, eutrophication and non-renewable depletion potentials. Each classification is expressed in reference to a specific pollutant: kilograms of *carbon dioxide* ($CO_2$) equivalent for global warming, kilograms of *trichlorofluoromethane* (CFC-11) equivalent for ozone depletion, kilograms of *ethylene* ($C_2H_4$) equivalent for photochemical oxidation, kilograms of *sulphur dioxide* ($SO_2$) equivalent for acidification, kilograms of *phosphate* ($PO_4^{3-}$) equivalent for eutrophication and kilograms of *antimony* (Sb) equivalent for non- renewable depletion.

Seven types of building technologies between thermal coatings and ventilated façades were considered as options to renovate the hospital of San Benedetto del Tronto: polyurethane, rock wool or glass wool thermal coat and ventilated façade with polyurethane, rock wool or glass wool as insulation and aluminum or ceramic as cladding. *SimaPro* and *EPD (2008)* method were performed. By carrying out a comparative analysis of the environmental results for all thermal coatings and ventilated façades studied, glass wool thermal coat had the lowest impact potentials on the environment, exception for ozone depletion category. Nevertheless, the type III EPD doesn't provide criteria or minimum requirements to be achieved by the product; subscribing an EPD is a voluntary process aimed at business-to-business and business-to-consumer communication, to encourage the continuous improvement of environmental performance of products over time.[7] By adopting *UNI TS 11300*, a second research had been carried out on the quantity of $CO_2$ (global warming impact category) released in the environment by managing the heating system during wintertime. A simpler building was considered in this project: a four flat condominium located in Bologna. The kilograms of $CO_2$ for every kind of building envelope were extended to both the useful lives of thermal coatings and ventilated façades, 10 and 25 years respectively. At the end, the amount of $CO_2$ derived from production (first analysis) and the managing of the heating system (second analysis) were summed: glass wool thermal coat resulted to be the less impactful on the environment related to the global warming category. As for the incidence of $CO_2$ from production on $CO_2$ from the heating system, ventilated façades showed a significant decrease passing from 10 to 25 years: that is consistent with the fact that ventilated façades have a lower environmental impact in the long run, while thermal coatings usually need to be replaced after about ten years.

In conclusion it is important to reiterate that a considerable amount of energy is consumed by the building sector at global level and future studies on buildings' sustainability are needed. As the building envelope can highly influence the energy consumption in buildings, innovative technologies such as *thermal energy storage* (TES) can help to boost the energy efficiency and to reduce the $CO_2$ emissions in this sector. An appreciable number of papers have been published on the application of *phase change materials* (PCMs) as passive systems in building envelopes. The combination of PCMs and construction materials is an efficient way to increase the thermal energy storage capacity of construction elements.

# APPENDIX

## PHASE CHANGE MATERIALS AND INTEREST IN BUILDING APPLICATIONS

*Phase change materials* (PCMs) are compounds applying the principle of *latent heat thermal storage* (LTHS) to absorb energy in large quantities when there is a surplus and releasing it when there is a deficit. Changing of material phase can be classified into four states: solid-solid, solid-liquid, gas-liquid and gas-solid. Only the solid-liquid variety can be used for building cooling or heating because the other varieties have technical limitations. PCMs are ideal products for thermal management solutions because they can control thermal fluctuations within a specific range. When the temperature rises above a certain point, the chemical bonds in the material will start to break up and the material will adsorb the heat in an endothermic process changing state from solid to liquid. As the temperature drops, the material will give off energy and return solid. This thermal process is explained and clarified in Figure 40. The combination of PCMs and construction materials is an efficient way to increase the thermal energy storage capacity of construction elements. The study is mostly focused on the effect of passive building systems through the integration of PCM enhanced building materials: PCMs are integrated into the building envelopes to increase the thermal mass. This is especially advantageous to lightweight constructions, which suffer from low thermal inertia. In summer, lightweight structures experiment large temperature fluctuations due to excessive overheating caused by a lack of thermal mass. As mentioned earlier, in summer PCMs would help rooms from overheating during the daytime, while in winter they may also reduce the need for heating during the night-time. This evaluation is linked to the importance of getting passive PCMs systems to completely discharge during night-time in warm periods. If the PCM is not able to completely solidify, the effectiveness of the system may be significantly reduced. On one hand night-time in summer would not always be sufficient for the PCM to fully solidify, on the other hand daytime in winter would not be enough to completely melt the PCM [17]. Experts come to understand that optimal phase change temperature is seasonal: complete discharge or complete absorbance of heat is difficult to obtain for a single PCM. Kalnæs et al. [18] suggest three temperature ranges for phase change temperature optimal in building PCM applications:

- Up to 21°C for cooling applications,
- 22-28°C for human comfort applications,
- 19-60°C for hot water applications.

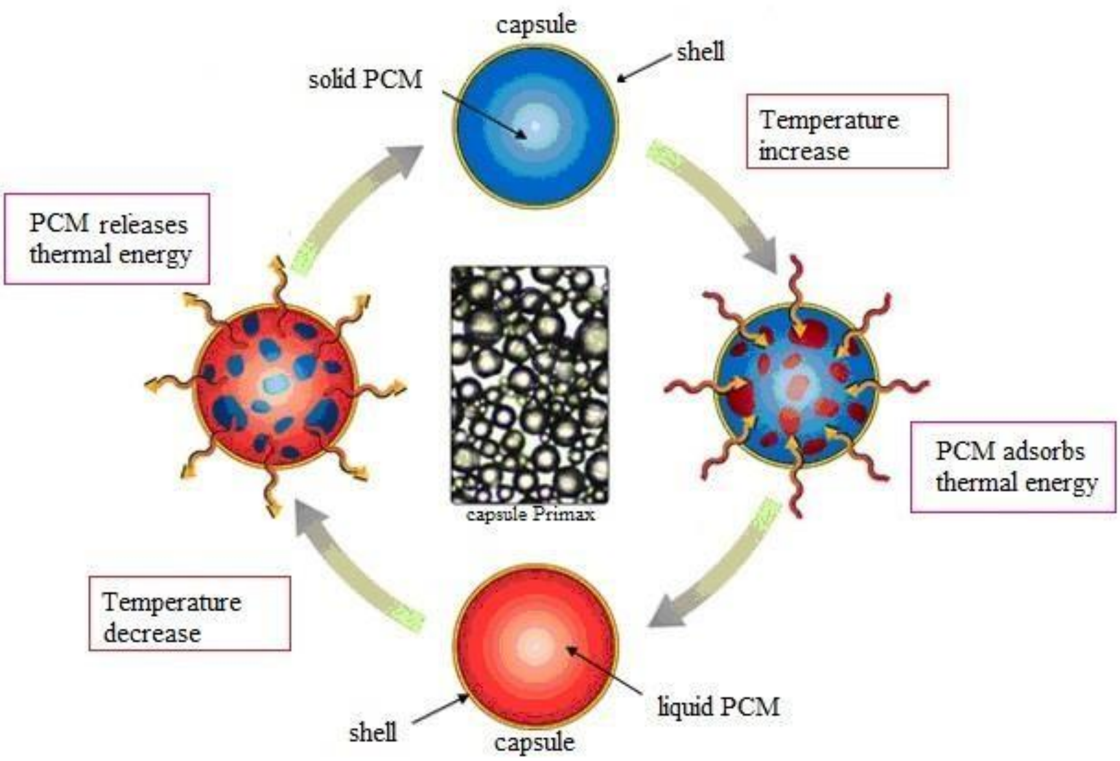


**Figure 40.** Cycle of PCMs [19].

### 1.5.1 CLASSIFICATION OF PCMs

Based on the chemical composition [20], PCMs are classified as organic, inorganic and eutectic as shown below in Figure 41.

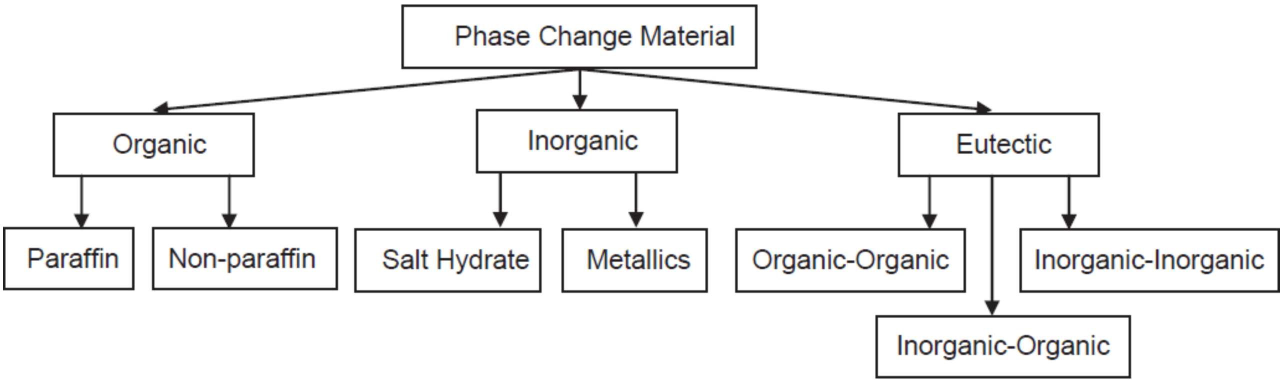


**Figure 41.** Classification of PCMs [20].

- **Organic PCMs (paraffines and non-paraffines)**

Organic materials are categorised into paraffines and non-paraffines, for the most part fatty acids: these last have received the most attention for use as PCMs in buildings. Commonly, organic present a congruent melting, or do not experience phase segregation, little or no supercooling and non-corrosiveness. Paraffines are composed by a mixture of mostly straight chain n-alkanes $CH_3$-$(CH_2)$-$CH_3$; their melting point and latent heat of fusion increase with the chain length. Paraffins have several advantages: they are safe, reliable, stable below 500 °C, show little volume changes on melting and have low vapor pressure in the melt form; these characteristics result in a long freeze-melt cycle. In spite of these advantages, paraffins have low thermal conductivities, are flammable and are non- compatible with the plastic containers. Compared to paraffines, fatty acids have higher heat of fusion, undergo cycles without losing their properties and do not experience the super-cooling effect. Nonetheless, their sharper phase change is offset by the drawbacks of being 2 to 2.5 times more expensive than paraffins and mildly corrosive [21].

**Benefits:**

- Large temperature range (from 20°C to 70°C) suitable for different applications.
- Inert.
- No phase segregation.
- Thermally reliable.
- Low vapour pressure in the melt form.
- Latent heat of fusion from 120 J/g to 210 J/g.
- High specific heat (particularly paraffines compared to salt hydrates).
- Non-corrosive (except for fatty acids like lauric acid, myristic acid, palmitic acid and stearic acid that are mildly corrosive).
- Suitable for construction material (except for paraffines that are not compatible with plastic containers).
- Small volume change.
- Limited or no supercooling during freezing.
- Non-toxic (except for non-paraffines that show varying level of toxicity).
- Stable below 500°C.
- Recyclable after disposal.

**Drawbacks:**

- Low thermal conductivity (0.15-0.17 W/(m K)).
- Moderately inflammable (crucial disadvantage for safety aspects).
- Paraffines are not compatible with plastic containers.

- **Inorganic PCMs**

Although inorganic PCMs have a smaller range of melting points compared to the organic ones, they are more suitable for building applications due to their wider range of phase change. Especially salt hydrates have a number of advantages that make them attractive for building applications like high latent heat of fusion per unit volume, small changes in volume on melting, high thermal conductivity, compatibility with plastics, not very corrosive, slightly toxic and non-flammable (the last property is of main importance). On the other hand, inorganic PCMs also exhibit high degree of sub-cooling, delay at the start of solidification and segregation. Due to their cost and non-sustainable origin (although salt hydrates are inorganic, they have a low impact on the environment), scientists are more interested in the development of organic PCMs. Inorganic materials are categorized into metallics and salt hydrates [21].

**Metallics**

- For building applications, they are not within the desired temperature range.
- They have severe weight penalties making them unsuited.

**Salt hydrates**

**Benefits:**

- High volumetric latent heat storage.
- High latent heat of fusion per unit volume.
- High thermal conductivity (about 0.5 W/(m K)).
- Low cost and easy availability.
- Compatible with construction materials.
- Suited for plastic containers.
- Non-flammable.
- Fast phase change.
- Low impact on the environment.

**Drawbacks:**

- Incongruent melting.
- Corrosive to metals.
- High vapor pressure.
- Long term degradation.
- Variable chemical stability

- High change of volume

- **Eutectic PCMs**

Eutectic PCMs are mixtures of organic and/or inorganic compounds (organic-organic, inorganic-inorganic or organic-inorganic); they are minimum melting compositions of two or more components, each of which melts and freezes congruently. While the most common organic eutectics that have been tested consist of fatty acids (like capric acid/myristic acid, lauric acid/stearic acid, myristic acid/palmitic acid and palmitic acid/stearic acid), the most commonly investigated inorganic eutectics are several salt hydrates [18].

**Benefits:**

- Sharp melting temperature.
- High volumetric thermal storage density.

**Drawbacks:**

- Limited data available.

### 1.1.2 CHARACTERISTICS OF PCMs for BUILDING APPLICATIONS

In order to be used for building applications, the PCM must possess certain desirable economic, thermal-physical, kinetic, chemical and environmental properties summarized from Kaenaes et al. [18] and Memon [20].

**Economic properties**

- Cost effective and commercially available, in the interest of making the technology more attractive and possible to use at a large scale.

**Thermal-physical properties**

- Phase change temperature matched to the application; it must be in accordance with the climate, location in the building and type of system where the PCM is used. The temperature range usually goes from 18°C to 40°C (the upper temperature limit is justified by the fact that the surface temperatures of roofs and external walls of buildings can reach 40°C).
- High heat of fusion per unit volume and unit weight, so that smaller size of container can be used.
- High thermal conductivity, in order to allow the heat to disperse through or leave the material rapidly, allowing the PCM to adsorb or release heat at a higher rate.
- High specific heat, so that additional energy (sensible heat) is available to the thermal energy storage system.
- Small volume change during phase transition and low vapour pressure at operating temperature to avoid containment problems.
- Congruent melting; PCM should melt completely during the phase transition.
- Cycling stability, so PCM is thermally reliable and it can be used in long run.

**Kinetic properties**

- Hight rate of nucleation as to avoid supercooling of PCM in liquid phase. Supercooling will alter the phase change temperature making PCM unsuitable. An attractive PCM should have an exact phase change temperature to be correctly selected for optimal design.
- High rate of crystal growth to optimize heat recovery.

**Chemical properties**

- Compatibility with construction/incapsulated material.
- Chemical stability and low corrosion rate in order to increase the lifetime of PCMs. Lifetime is about 10000 cycles (melting/freezing) corresponding to 30 years.
- Non-toxic, non-flammable and non-explosive to respect strict regulations about safety. These properties have to be assured both during fire and in case of rupture during regular use.

**Environmental properties**

- Low environmental impact: production and service life of PCM should not release dangerous emissions to the environment.
- Recycle potential.

In favour of energy savings and increase in overall indoor thermal comfort, PCMs can be used in building applications: thanks to PCMs may be possible to maintain a steady temperature around the comfort zone for longer periods without relying on *heating, ventilation and air conditioning* (HVCA) systems. PCMs will be selected in accordance with the desired melting/freezing point conducive to the temperature stability around the comfort temperature. The main parameters piloting the choice of a PCM are:

- Phase change temperature,
- Enthalpy curve,
- Total latent heat capacity.

Concerning the position of PCMs in buildings, they should be placed where they can fully adsorb the energy coming from the sun like wallboards on walls or roofs and windows.

### 1.5.3 OPTIMUM PCMs MELTING TEMPERATURE

At global level, a considerable amount of energy is consumed by the building sector. As the building envelope can highly influence the energy consumption in buildings, innovative technologies such as *thermal energy storage* (TES) can help to boost the energy efficiency and to reduce the $CO_2$ emissions in this sector. An appreciable number of papers have been published on the application of PCM as passive systems in building envelopes; researchers agree that a key factor to increase the energy performance in buildings is the choice of the PCM melting temperature in different climate conditions. Saffari et al. [22] found out the optimum PCM melting temperature according to the outdoor boundary conditions for different cities around the world and evaluated the corresponding energy saved, while still ensuring indoor thermal comfort, in both heating dominant and cooling dominant climates. Table 65 shows the results early mentioned.

| Climate zones | Cities | Melting point for heating & cooling [°C] | Total heating & cooling savings | | Climate zones | Cities | Melting point for heating & cooling [°C] | Total heating & cooling savings | |
|---|---|---|---|---|---|---|---|---|---|
| | | | [kWh] | [%] | | | | [kW h] | [%] |
| Am | Manaus | 26.00 | −3984 | −9.0% | Csb | Antofagasta | 20.00 | 133 | 5.1% |
| | Freetown | 26.00 | −1924 | −4.3% | | Ankara | 20.00 | 1813 | 2.0% |
| | Colombo | 22.44 | −32 | −0.1% | | San Francisco | 20.06 | 760 | 3.8% |
| Aw | Brasilia | 25.88 | 1376 | 17.5% | Csa | Tehran | 20.00 | 922 | 2.0% |
| | Bangui | 25.94 | 589 | 1.5% | | Seville | 26.00 | 811 | 3.5% |
| | Kolkata | 26.00 | 685 | 1.4% | | Cagliari | 24.44 | 450 | 1.7% |
| As | Fortaleza | 24.13 | 113 | 0.2% | Cwa | Rangpur | 25.50 | 554 | 1.4% |
| | Indore | 26.00 | 1023 | 3.3% | | Hong Kong | 20.13 | 343 | 1.3% |
| | Malindi | 25.81 | 157 | 0.4% | | Ankang | 25.19 | 1013 | 2.3% |
| Af | Kuala Lumpur | 25.38 | 171 | 0.4% | Cwb | Huili | 20.00 | 836 | 4.3% |
| | Singapore | 25.50 | 213 | 0.4% | | Jiulong | 20.00 | 1705 | 2.2% |
| | Puerto Barrios | 25.63 | 3054 | 8.0% | | Addis Abeba | 26.00 | 166 | 12.0% |
| BsK | Albuquerque | 20.00 | 1381 | 2.5% | Dfa | Chicago | 25.13 | 1704 | 1.4% |
| | Midland | 20.00 | 1300 | 3.0% | | Omaha | 26.00 | 1952 | 1.5% |
| | Ceduna | 25.06 | 987 | 7.3% | | Cleveland | 25.63 | 3492 | 2.8% |
| BSh | New Delhi | 25.38 | 619 | 1.4% | Dfb | Montreal | 25.44 | 3565 | 1.9% |
| | Dakar | 25.50 | 561 | 1.9% | | Moscow | 24.31 | 2117 | 1.2% |
| | Del Rio | 25.63 | 825 | 2.4% | | Stockholm | 21.50 | 5741 | 3.3% |
| BWh | Abu Dhabi | 26.00 | 975 | 1.8% | Dwa | Beijing | 25.63 | 3099 | 3.3% |
| | Jaisalmer | 25.94 | 770 | 1.4% | | Incheon | 20.00 | 883 | 1.0% |
| | Phoenix | 26.00 | 1018 | 2.7% | | Pyongyang | 25.63 | 2892 | 2.6% |
| BWk | Calama | 25.63 | 317 | 7.5% | Dfc | Yellowknife | 23.75 | 5537 | 1.3% |
| | Las Vegas | 26.00 | 1018 | 2.6% | | Anchorage | 23.94 | 5709 | 2.5% |
| | Yumenzhen | 26.00 | 5213 | 3.3% | | Kiruna | 20.19 | 3045 | 1.0% |
| Cfa | Brisbane | 25.19 | 656 | 6.9% | Dwb | Linjiang | 25.00 | 1848 | 1.0% |
| | Madrid | 20.00 | 1093 | 2.6% | | Linxi | 26.00 | 3865 | 1.9% |
| | Tokyo | 20.00 | 791 | 1.2% | | Pingliang | 20.00 | 2292 | 2.1% |
| Cfb | Berlin | 24.38 | 2054 | 1.7% | – | – | – | – | – |
| | Johannesburg | 25.56 | 4000 | 22.7% | – | – | – | – | – |
| | Paris | 24.06 | 1564 | 1.9% | – | – | – | – | – |

**Table 65.** Optimum PCM melting temperature and energy savings for different cities. [22]

Data reveals the optimum PCM peak melting temperature:

- 26°C (range 24-28°C) in cooling dominant climates (Koppen-Geiger classification A and B).
- 20°C (range 18-22°C) in heating dominant climates (Koppen-Geiger classification C and D).
- 23°C in Anchorage (class D), 24°C in Paris (class C) and 25°C in Chicago (class D).

The table above also shows the total heating and cooling savings exception for Manaus, Freetown and Colombo (equatorial-monsoonal climate zone class A) where the application of PCM is not feasible because it causes the increase of the annual energy consumption.

### 1.5.4 PCMs BUILDING IMPLEMENTATIONS

Heating, ventilating and air conditioning (HVAC) systems account for 60% of the total energy consumed in buildings. Therefore, heat storage is a very interesting technique to decrease energy use in the buildings and to reduce the cost of operation of buildings. As shown in Figure 42 cooling strategies can be classified into two major groups, including active and passive. Active strategies cover all conventional HVACs (e.g. AHU and chillers). By contrast, passive cooling is attributed to the utilization of energy available from the natural environment rather than the consumption of conventional energy resources [23].

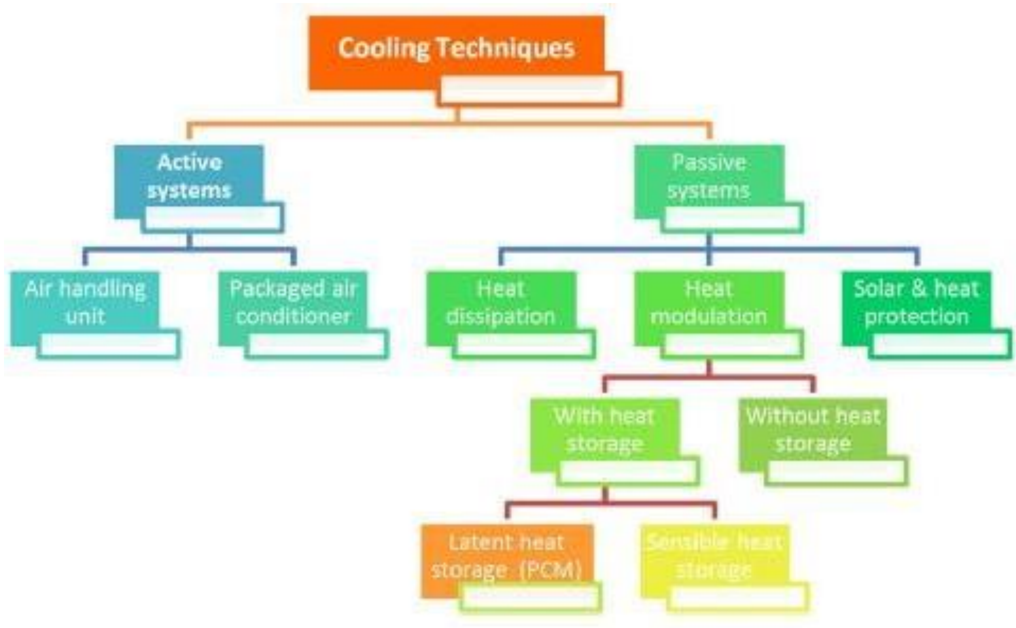


**Figure 42.** Different types of cooling techniques. [23]

Thermal energy storage (TES) can be divided into sensible heat storage and latent heat storage systems.

In sensible heat storage (SHS), heat can be stored in a temperature increase in the material. The specific heat of the medium, temperature variation and the quantity of the material are the principal factors that determine the amount of heat storage capacity of the SHS, as shown in Eq:

$$Q = \int_{T_1}^{T_2} mc_p \mathrm{d}T = mc_p(T_2 - T_1)$$

In contrast, in latent heat storage (LHS), thermal energy is reserved (or released) when the phase of the material changes from one state to another (e.g. solid to liquid). The amount of stored energy can be determined by:

$$Q = \int_{T_i}^{T_m} mc_p \mathrm{d}T + ma_m \Delta h_m + \int_{T_m}^{T_1} mc_p \mathrm{d}T$$

$$Q = m[c_{sp}(T_m - T_i) + a_m \Delta h_m + c_{Lp}(T_f - T_m)]$$

The materials used for latent heat energy storage (PCM) have the characteristic of absorbing or releasing thermal energy via temperature variations in controlled conditions. In contrast to customary construction materials (e.g. concrete), PCMs can store thermal energy in both sensible heat as well as latent heat.

For example, ordinary building materials such as concrete and gypsum only represent the sensible heat storage capacity, which varies approximately between 0.75 and 1 kJ/(kg K) whereas, some average paraffin materials, which undergo phase change have latent heat storage capacity of approximately 110 kJ/kg. This means that due to very high heat storage potential, a much smaller volume of the material is needed to store the same amount of energy: a wall with 25 mm thickness incorporated with PCM is able to reserve the same amount of thermal energy as a concrete wall with 420 mm thickness.

Another advantage of PCM is that their phase change is characterized by an almost constant temperature and a generally negligible volume changes. Moreover, some investigations have found that PCMs integrated into buildings can mitigate energy by 10% to 87% for cooling purposes. As a result, PCMs have been recognized as one of the most progressive materials to enhance energy efficiency and sustainability in buildings, especially for heating and cooling. [23]

Although this state of the art of PCM review will especially be focused on building integration in recent years, their application has grown incrementally in different industries, such as the space industry, electronic industry, solar cooling and solar power plants, solar dryers in agricultural industry, photovoltaic electricity systems, preservation of food and pharmaceutical products, waste heat recovery systems and domestic hot water.[23]

To summarize, some of the passive cooling advantages in buildings are:

- reduction of peak power for heating and cooling,
- possibility to shift peak heating and cooling loads to the low tariff hours,
- shifting temperature peaks to non-working hours,
- improvement of indoor environment,
- efficient utilization of passive heating and cooling loads.

**Methods of incorporation**

The PCM can be incorporated in construction materials and elements by direct incorporation, which is known as shape-stabilization, immersion, encapsulation and form stable composite PCMs.

**Shape-stabilized PCM**

In this technique, shape stabilization supports such as high- density polyethylene (HDPE), styrene, and butadiene are used to fabricate shape-stabilized PCM. The PCM and the supporting material are melted and mixed with each other at high temperature followed by cooling the supporting material below the glass transition temperature until it becomes solid. The shape stabilized PCM has the following prominent features: [20]

- large apparent specific heat,
- appropriate thermal conductivity,
- keeping the shape stabilized during phase transition process,
- thermally reliable (melt/freeze cycle) over a long period,

- no need for container,
- the mass proportion of PCM can be up to 80%.

An example of one of the research works focusing on the development of shape stabilized PCM is reported here.

Inaba and Tu studied the thermophysical properties of shape stabilized PCM. The shape stabilized PCM consists of paraffin as thermal storage material and HDPE as supporting material. Moreover, little quantity of Ethylen-α olein was added to the mixture to reduce oozing rate of the paraffin. It was found that the developed shape stabilized PCM contained 74wt% paraffin, had a melting temperature of 54.8 °C and heat of fusion 121.5kJ/kg.

**Encapsulation**

Encapsulation of PCM is usually preferred to other techniques because of:

- low potential of leaking during changing of the PCM phase to liquid,
- can prevent the low viscous liquids from diffusing throughout the material,
- enlarging the surface area, encapsulation can increase the thermal conductivity, which means increasing the heat transfer between the PCM and surrounding environment,
- isolation of PCM from harmful environmental factors,
- compatibility between PCM and surrounding materials,
- decline in corrosion,
- managing volume variation during state changes.

The material used to encapsulate should not react with the PCM or show signs of deterioration over time. Currently, two main methods are used for encapsulating PCMs, i.e. micro and macro encapsulation. These two methods give various sizes and shapes of the PCMs and affect how PCMs may be incorporated into a material or construction.

**Microencapsulation**

Microencapsulation of PCMs involves packing the PCM materials in capsules which range from less than 1 μm and up to around 300 μm. [18]

The process can either be performed physically or chemically: the former includes coating, air-suspension coating, centrifugal extrusion, vibrational nozzle and spray drying while the latter method includes coacervation, complex coacervation and interfacial polymerization. [24]

The shell materials commonly used for microencapsulation consist of organic polymers or silica. In the microencapsulation procedure, individual particles or droplets are coated by a continuous film to form a capsule with the size of a micrometer, known as a microcapsule. Two main parts can be observed in microencapsulation: the PCM, which is the core, and the shell, which can be a polymer or an organic substance. The shape of microencapsulation is not limited, it can be either a regular (e.g., tubular, oval or spherical) or an irregular shape.

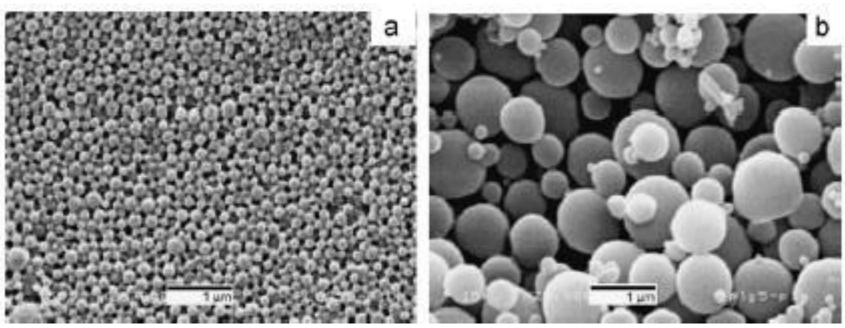


**Figure 43.** SEM profile for (a) spray-dried (b) concervated microparticles. [20]

Microencapsulation has the following advantages: [20]

- prevents the leakage of PCM during phase transition by building a barrier thereby increasing its chances of incorporation into various construction materials,
- provide high heat transfer rate through its larger surface area per unit volume,
- capable of resisting volume change during phase transition,
- improved chemical stability.

and disadvantages:

- lower latent heat storage capacity per unit volume and unit weight than the pure PCM due to the adding of the encapsulating material,
- the rigidity of the shell prevents natural convection and therefore decreases the heat transfer rate,
- microencapsulation may affect the mechanical properties of the construction materials,
- high investment cost renders its feasibility to reach commercial state.

**Macroencapsulation**

In this technique, a significant quantity of PCM (up to several liters) can be packed in a container such as tubes, spheres and panels for subsequent used in construction elements. [20] The size of these containers is usually larger than 1 cm.

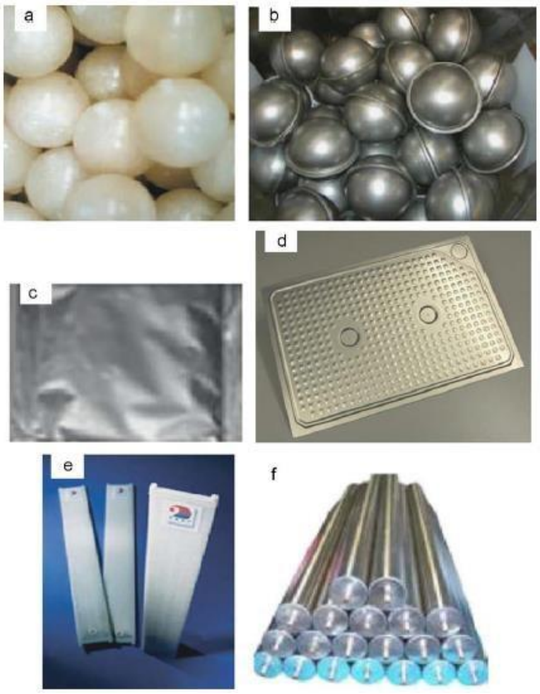


**Figure 44.** (a) metal ball encapsulated, (b) spherical PCM balls, (c) PCM in aluminium, (d) PCM in aluminium panels, (e) PCM in Polypropylene flat panel, (f) PCM tube encapsulation. [18]

Macroencapsulation has the following advantages:

- easier to ship and handle,
- can be designed to fit the intended application,
- improves compatibility of PCM with the surrounding by acting as a barrier (however, the container should be compatible with the surrounding),
- reduces external volume changes which are important for building application.

and disadvantages:

- poor thermal conductivity,
- affinity towards solidification at the corners and edges, thereby preventing an effective heat transfer,
- the size of the macrocapsules imply that they have to be protected against destruction or perforation.

Therefore, the encapsulation must be optimized for effective heat transfer rate and at the same time it should be corrosion resistance, thermally stable and reliable.

**Form-stable composite PCM**

In literature the terms form-stable and shape-stabilized PCMs have been used interchangeably, whereas uses the term form-stable composite PCM to define a composite PCM which retain an optimum/maximum percentage of PCM and shows no sign of leakage when the temperature of the composite is above the melting point of PCM. Also, it is not necessary for the supporting material in form-stable composite PCM, as opposed to shape-stabilized PCM, to melt. [20] The form stable composite PCM can be obtained by natural immersion or vacuum impregnation. The natural immersion is simple and easy to use. However, the retention capacity of building materials to store thermal energy is low. Therefore, the retention capacity of porous building materials can be increased through vacuum impregnation method. In review papers on thermal energy storage using PCM, the literature on form stable composite PCM is scarce.

A short analysis of diatomite and expanded perlite and graphite as supporting materials for PCM follows.

Diatomite is the skeletal remains of single celled plants called diatoms. Diatomite finds its application in many fields such as construction material, heat, cold and sound insulator, filler absorbent, abrasive and ingredient in medicine. Furthermore, due to its highly porous microstructure, high absorptivity and inertness, it is being used as a supporting material for storing PCM.

Perlite, anamorphous volcanic glass, is one of the nature's most versatile and efficient minerals having relatively high-water content. When this amorphous volcanic glass is heated rapidly at 850–1150 °C, it expands up to 10–20 times its original volume due to vaporization of combined water. The resulting product, expanded perlite, has unique characteristics such as lightweight, highly porous, and high fire resistance. Which makes it a first-class choice for diverse applications such as thermal energy storage applications, construction, filtration, horticulture, industrial, and insulation. Various researchers have successfully utilized expanded perlite as supporting material for PCM.

Expanded graphite is prepared from natural graphite through chemical oxidation in the presence of concentrated sulfuric acid/nitric acid/mixture of sulfuric and nitric acid, followed by drying up process in the oven and finally by rapid heating in a furnace at high temperature (e.g. 900°C). It has good absorption ability and high thermal conductivity. Therefore, it has been used in thermal energy storage applications as a supporting material for PCM as well as to improve the thermal conductivity of the system. [20]

It is worth mentioning that both direct and immersion techniques incorporate PCM directly into the conventional construction materials.

**Direct incorporation**

This is the simplest, practicable and economical method in which PCM is directly mixed with the construction materials for example gypsum, cement paste, mortar or concrete during pro- duction. For successful utilization of PCM especially into cement-based materials it should not:

- affect the bonding between the paste and the aggregate,
- affect the mechanical properties,
- affect the durability properties.

Many researches in this area ended with conclusion that that direct incorporation of PCMs may involve leakage after many work cycles [25].

**Immersion**

In the immersion technique, the construction elements (concrete and brick blocks, wall boards), which are dipped into the liquid PCM, absorb the PCM by capillary action. It is reported that PCM may leak especially after subjected to large number of thermal cycles. Also, it may affect the mechanical and durability properties of the construction elements.

### 1.5.5 MEASUREMENTS OF THERMOPHYSICAL PROPERTIES

The correct design of the building or storage system with integrated PCMs requires correct knowledge of the thermal properties of the PCMs used. For example, the single data points, the phase change enthalpy at the melting temperature or the heat of fusion do not describe PCM properties with sufficient accuracy to perform dynamic simulations of a room or a whole building containing PCM. The phase change occurs in a temperature range and not at a constant temperature level, and therefore specific heat capacity or enthalpy of this type of material has to be known as a function of temperature. Literature review indicated that the following methods are most often used to measure specific heat capacity of pure PCMs and their composites: differential scanning calorimetry (DSC) and T-history method.

### Differential scanning colorimetry

*Differential Scanning Calorimetry* (DCS) is an analytical technique. The term was coined to describe equipment having the capability to directly measure the energy and allow accurate measurement of heat capacity. DSC measures the temperatures and heat flows associated with material changes as a function of time and temperature in a controlled environment. The measurements provide qualitative and quantitative data about physical and chemical changes that involve endothermic or exothermic processes. DSC can only be used for testing small samples of PCMs. DSC can only be used for testing small samples of PCMs. Through DSC it is possible to obtain melting temperatures and the heat of fusion. For this purpose, DSC is the most used method. According to Kuznik et al. [25], the name differential scanning calorimetry is very clear:

Calorimetry: The measurement of the quantity of heat absorbed or released by a sample subjected to temperature change.

Differential: The above measurements on sample are done with respect to reference sample with known properties.

Scanning: The thermal excitation with a linear temperature ramp.

Regarding DSC method, two modes can be distinguished: dynamic mode and isothermal step mode. In number of publications, the dynamic mode is used to determine the specific heat capacity of pure PCMs and PCM composites. The shortcomings and some sensitivity analysis of dynamic DSC measurements are discussed and presented in [26]. Authors point out, that measurements with different heating rates and different sample masses gave results that differ considerably from each other. In the article, an explanation for the discrepancy of the results can also be found. Finally, the conclusion that in context of PCM, the dynamic mode is not the proper approach can be found and instead of the dynamic mode an isothermal step mode or T-history method should be used. In the article, it is also stressed that DSC in general is not suitable for heterogeneous materials. This conclusion should be considered with special care.

**T-history**

Another method, the T-history method has been proposed in reference.

T-history method proposed in reference has the following advantages: a large sample size of organic, inorganic, encapsulated or composed PCM can be measured, ranges of heating and cooling rates and temperatures are sufficiently large for various PCM applications, the instrumentation and experimental set-up is simple and inexpensive.

This method is efficient at determining fusion enthalpy, specific heat and thermal conductivity for large PCM samples. Nevertheless, there is still no commercial T-history equipment available yet.

### 1.1.6 PCMs IN BUILDING APPLICATIONS

The thermal mass concept helps PCM manage the thermal conditions inside a building. The building structure itself constitutes a source of thermal energy storage and plays a key role in buffering heat to mitigate external heat flows and reduce indoor temperature swings. Therefore, the structure acts as a heat sink during warm periods.

An obvious merit of increasing the thermal mass can be observed in light-weight building structures that suffer from low thermal inertia, which promotes considerable temperature fluctuations in the hot season due to overheating by solar radiation. Moreover, it can be useful in the winter when PCMs can act as insulators, decreasing the heating load. As result, PCMs can prevent over heating during the daytime on hot days and potentially reduce the heating needs during the nighttime in the cold season. [23]

Zhu et al. [27] presented an overview of research conducted on PCMs with regards to their dynamic characteristics and energy performance in buildings.

**Free cooling**

Free cooling systems with PCMs work by storing outdoor coolness (e.g. during the night) and release the coolness indoors during the day. The PCM can then be used during the day to absorb the heat from e.g. passing air in a ventilation system or water in a pipe system, and stored as latent heat, to cool the building in the day when temperatures are higher and the need for cooling increases. These systems work as long as the ambient temperature allows the PCM to freeze and melt over the day, i.e. the ambient temperature must be above the phase change temperature during the day and below during the night (Figure 45) (Zalba et al.). [28]

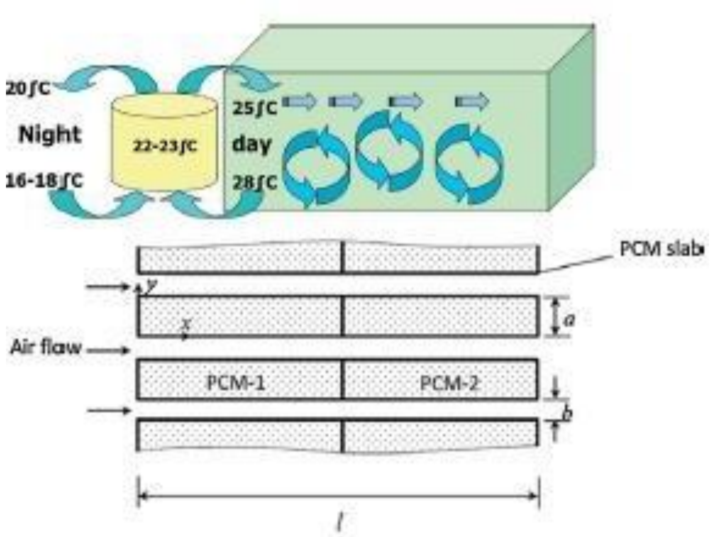


**Figure 45**. Schematic of a free cooling air conditioning system according to Zalba and Mosaffa. [28]

Mosaffa et al. [28] described a free cooling system using PCM slabs separated by air gaps for air to flow through (Figure 45). The model developed from this can be used to evaluate performances of latent heat storage systems for free cooling air conditioning systems.

**Peak load shifting**

Peak loads that hit during the day put pressure on the electrical grid and also lead to the need for heating, ventilation and air conditioning (HVAC) systems being dimensioned for higher heating or cooling loads. Ultimately, this could lead to a need for more power generation facilities being built. By shifting the peak load away from the peak hours of electrical demand using PCMs, the peak load may be divided throughout the day reducing the highest peaks (Halford and Boehm). [29] Figure 46 illustrates how the peak maybe both reduced and shifted by the use of PCMs. Sun et al. [30] reviewed strategies involving PCMs for peak load shifting and control that have been tested so far. From the studies reviewed, peak cooling load reductions ranging from 10 to 57% with no or simple control strategies were found. The greatest reductions were found in cases where the PCM was compared against an insulated lightweight construction, while the lowest reduction was found when comparing against structures containing more mass, e.g. concrete. However, the cost saving potential of these systems could be further improved if more sophisticated load shifting control strategies were developed.

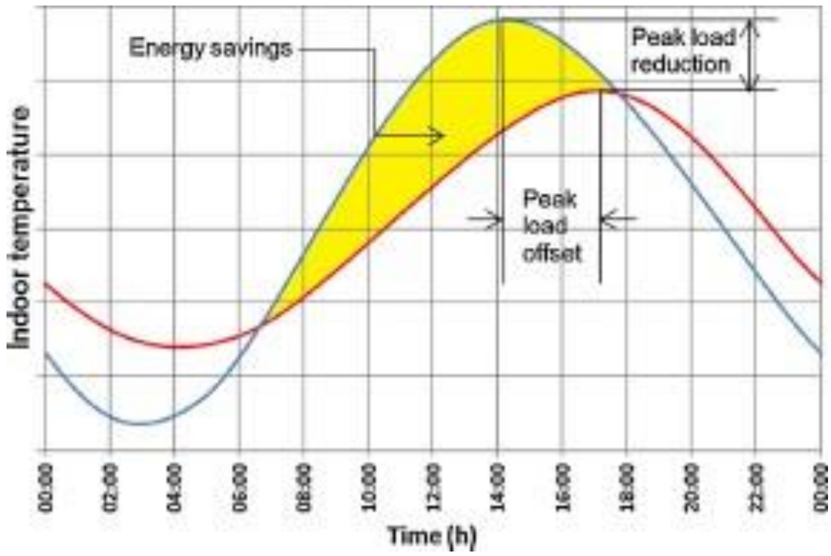


**Figure 46.** Illustration of peak load offset and peak load reduction. [18]

### Thermal comfort control

Though PCMs show potential for energy savings, another important factor to highlight is the benefits PCMs may have towards increasing the overall indoor thermal comfort. Lan et al. [31] showed a correlation between workers' performance and productivity compared to the sensation of thermal comfort due to shifting temperatures. Seppänen and Fisk [32] showed that elevated air temperatures had a negative effect on performance and productivity. When temperatures increased up to 20°C there was an increase in working performance. However, when temperatures increased above 23°C there was a decrease in productivity. Maintaining a steady temperature around the comfort zone for longer periods without relying on HVAC systems may be possible with PCMs. With PCMs installed temperature fluctuations are reduced. The focus should be placed on selecting a PCM within the desired melting/freezing point so temperatures stay stable around the comfort temperature. This will benefit the indoor climate in two ways:

- Temperature will be held more stable, reducing the feelings of thermal discomfort due to temperature fluctuations throughout the day
- The peak temperature will be reduced and should not reach a temperature which leads to increased thermal discomfort

Another possible benefit of PCMs can be that they lead to a more uniform temperature between surfaces and air temperature, reducing thermal discomfort from radiative heat.

**Active building system**

The storage capability of PCMs can be integrated into systems such as e.g. solar heat pump systems, heat recovery systems and floor heating systems. Such systems can be combined to achieve a peak load reduction. However, if they are made even more effective, they can achieve further savings through reduced electrical demand for HVAC systems. An example of a radiant floor incorporating PCMs in an active system has been described by Ansuini et al..[33] The system investigated consists of a lightweight piped radiant floor system with an integrated PCM layer aimed at buffering internal gains during the summer season without affecting the winter warming capacity.

**HVAC**

With the integration of PCM in HVAC system it is possible to reduce the indoor air temperature. While the HVAC is operating, the PCM’s state is solid. When the indoor temperature increases, the air transfers its thermal energy to the PCM to be cooled.

Through this process, a promising solution can be found for the mismatch correction between the supply and demand of electricity because PCM provides the opportunity to shift the energy demand from high cost tariff periods to off-peak times. This is known as "peak shaving" or "peak shifting". While this strategy can be utilized for both cooling and heating, it is better known for cooling purposes. By employing this strategy, HVAC systems can fully operate during off-peak periods to meet the cooling needs as well as charge the PCM. That is, the PCM can provide the total cooling load during peak hours while the HVAC system is completely out of operation. From an economic perspective, buildings can benefit from lower electricity tariffs (lower operation fees) during off-peak periods. The Figure. 46 depicts how the peak may be reduced and shifted by the use of PCMs.

**Heat pumps**

The use of heat pumps for buildings cooling and heating is assessed as efficient technology.[34] Additionally, it may be even more productive if heat pump cooperates with thermal energy storage system. Selected examples of researches in this area are presented in this section. Agyenim and Hewitt [35] studied RT58 PCM as a part of a wider study focused on investigation proper phase change material to take advantage of off-peak electricity tariff. Based on obtained results, the authors identified quadratic relationship between heat transfer coefficient and the inlet heat transfer fluid temperature (within temperature range 62-77 °C). They also concluded that it is possible to reduce storage size by 30%, but it is required to heat transfer techniques to charge and discharge heat form the storage. Zhu et al. [36] carried out numerical simulation and analysis on the system of ground source heat pump integrated with PCM storage tank to study optimal control method for this system. They conducted for different conditions - under different cooling storage ratios. They presented an example of optimal usage of the combined system. The scheme of the combined system is presented on the Fig.10.

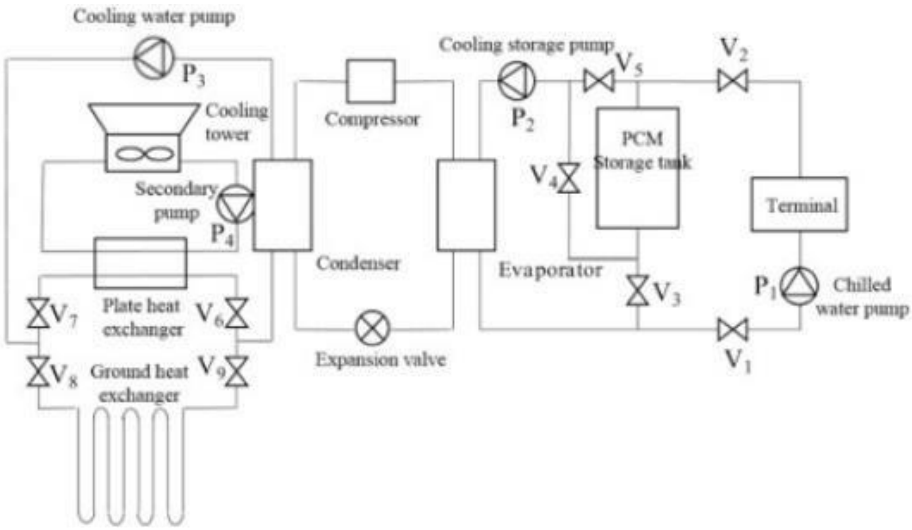


**Figure 47.** Scheme of combined system of ground source heat pump integrated with PCM.[34]

The authors concluded that use of proposed system in comparison to ground source heat pump without PCM storage is characterized by better reliability of the operation performance and reduction of energy consumption and operation cost. Comparison of different cooling storage ratios showed that this factor affects the performance and economy. Optimal cooling storage ratio depends on building type, location and system utilization mode.

### Solar thermal energy storage

PCMs hold the ability to store energy given off by the sun. Where solar cell panels can produce energy during hours of solar radiation, PCMs can store some of the excess energy and release it at a more needed time of the day. This can be combined with different energy distribution systems such as a heat pump for PCMs to best utilize the solar energy it.

Mahfuz et al. [37] conducted experimental study to test water heating system based on shell and tube thermal energy storage system with paraffin wax to analyze its performance for solar water heating application, Figure 48.

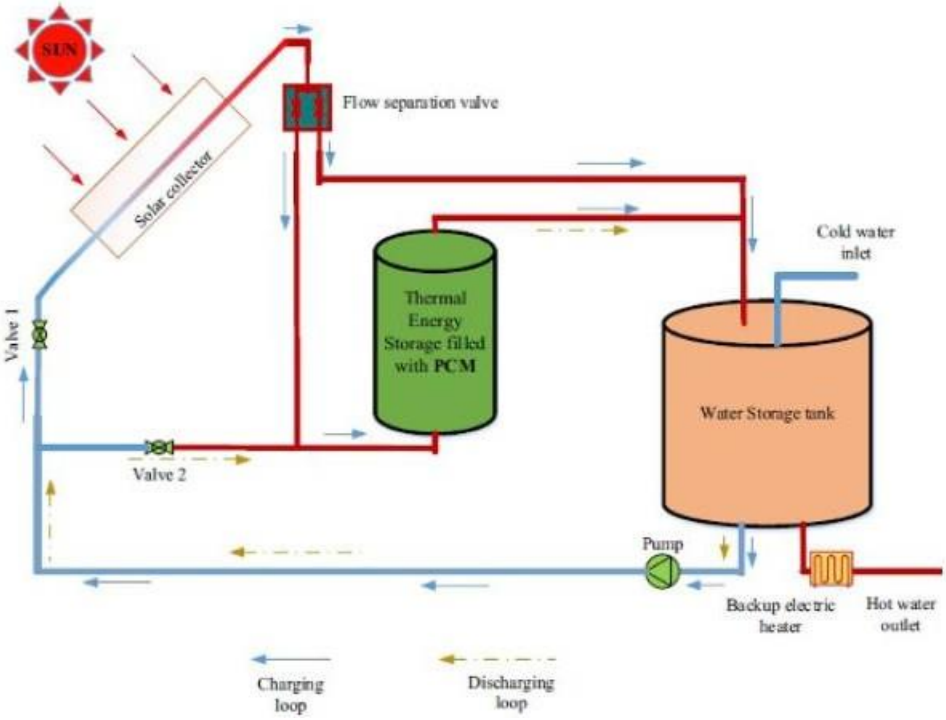


**Figure 48.** Solar heating water system with the thermal energy. [34]

Based on obtained results authors suggested some recommendations for future work related to: optimization of pipe diameter, testing different types of PCMs, testing different heat transfer fluids alternative for water, increasing of heat transfer coefficient.

**Passive building systems**

Passive building systems and their use have attained the most interest so far. For passive applications, PCMs are integrated into the building envelopes to increase the thermal mass. This is especially beneficial in lightweight constructions, which suffer from low thermal inertia. A known issue for these buildings is large temperature fluctuations in the summer due to excessive overheating caused by a lack of thermal mass.

This is usually true in cold climates where buildings have been built according to passive house standards and therefore often involving large amounts of insulation - to reduce heating loads in the winter - but small amount of thermal mass. The materials incorporating PCMs will melt during the daytime and solidify during nigh time. This will help rooms from overheating during the daytime in warm months and may also reduce the need for heating during nigh time in the winter. An issue that has been brought up is the importance of getting passive PCM systems to completely discharge during nigh time in warm periods. If the PCM is not able to completely solidify, the effectiveness of the system may be considerably reduced. This point makes PCMs more effective in climates with large daily variation in temperatures. For areas where the discharge does not happen naturally, cool air has to be supplied during nigh time to reset the PCMs completely. It is better to underline that the activation of latent heat storage in all presented cases is due to passive activation, and it means that thermal mass represented by the constructions is heated up or cooled down only due to indoor temperature fluctuations that were not caused by any mechanical additional cooling and heating means.

Most of the studies have been focused on PCM integration into the construction elements of building because commercial products were inadequate to deliver heat to the building after PCM was melted.

**Walls**

The most common solution for implementing PCMs into buildings so far is by installing PCM enhanced wallboards towards the interior side of the building envelope.

Memon et al. [20] conducted thermal performance tests (small-scale experiments) of a lightweight aggregate concrete (LWAC) containing macro encapsulated paraffin–lightweight aggregate (LWA) for wall application. Their study also assessed the economic and environmental aspects of the proposed PCM application for a residential building in Hong Kong. The results of the indoor test revealed that the macro encapsulated paraffin–LWA panel was able to decrease the interior temperature at the room center and at the internal surface of the panel by 4.7 °C and 7.5 °C, respectively. The recovery period of the LC–100% PCM–LWA was 29 years, while the average life span of a residential building in Hong Kong is 60 years. Therefore, from an economic point of view, the application of macro encapsulated paraffin–LWA in LWAC building walls was proven to be feasible.

Kong et al. [38] investigated the thermal performance of two new PCM systems incorporated into building envelopes using full scale experiments and numerical methods. In the experimental study, panels containing Capric acid (PCMOW) as well as Capric acid and 1-dodecanol (PCMIW) were installed on the outside and inside surfaces of the walls and roofs, as shown in Figure 49.

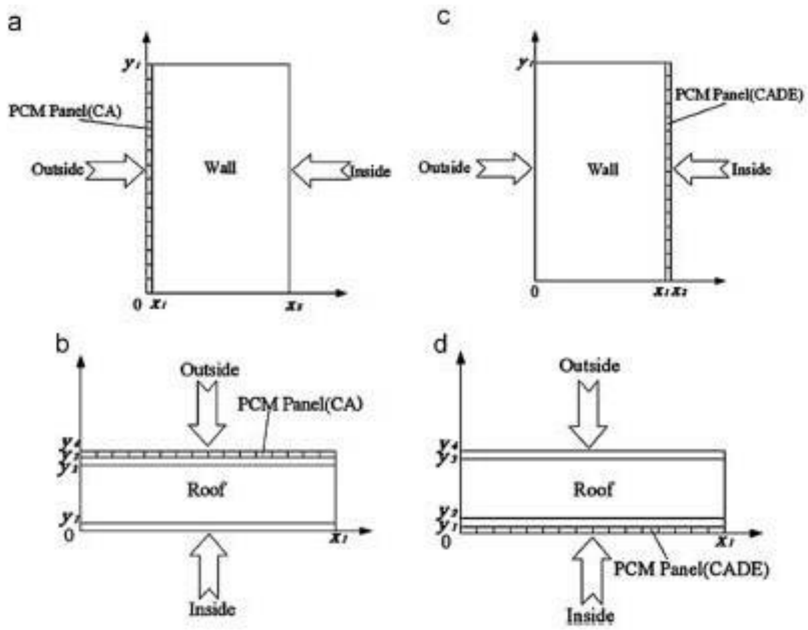


**Figure 49.** Structure of the building envelope for (a, b) the PCMOW and for (c, d) the PCMIW. [23]

In the numerical study, which was conducted using computational fluid dynamics (CFD) software, the internal temperature development, temperature variation and thermal energy saving were analyzed in two ventilation modes including free cooling and opening the window and door at night. The results showed that the thermal performance of PCMIW was better than PCMOW, particularly for the condition of opening the window and door at night; however, an interior retrofit in current buildings was required for the PCMIW application. Nevertheless, the PCM panel application in both walls and roof was found to be effective.

In a recent study conducted by Barreneche et al. [39], the thermal and acoustic performance of a shape stabilized PCM layer for an intermediate wall of a building was experimentally investigated in Spain. The new shape stabilized PCM was composed of a polymeric matrix, 12% paraffin PCM and electric-arc furnace dust (EAFD) (a waste from the steel recycling process). The thermal study involved in situ measurements of ambient temperature, humidity and wall temperatures for two identical cubicles with and without PCM dense sheet. The results of the thermal experiment demonstrated the potential of the PCM dense sheet to reduce the interior temperature up to 3 °C, Figure 50.

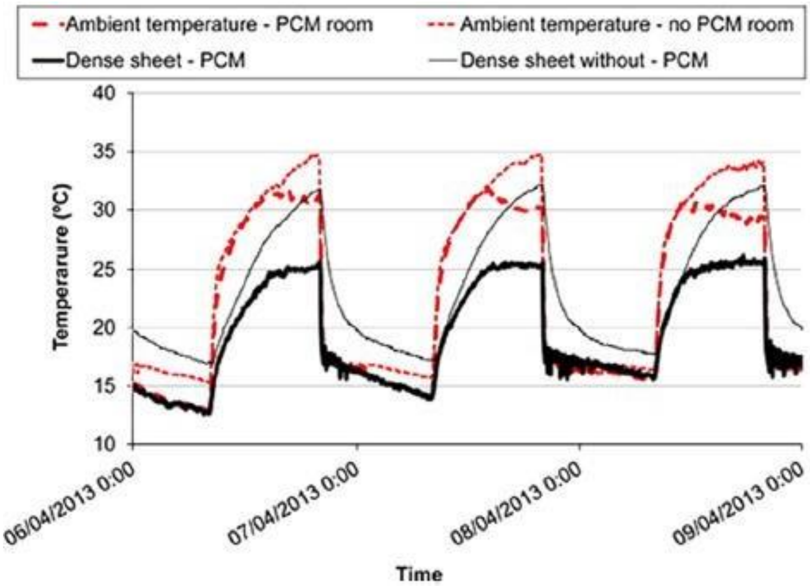


**Figure 50.** Temperature variations inside the PCM cubicle and the reference cubicle and directly measured temperature on the dense sheets. [23]

The acoustic insulation capability of the PCM cubicle was found to be more than the reference cubicle (up to 4 dB) due to the EAFD content.

Ascione et al. [17] studied the effect of using PCM on the exterior building envelope during the cooling season in five Mediterranean cities. Based on a “one-dimensional conduction finite difference” method, as a heat balanced algorithm, the building behavior and a comparison of the phase change temperature, the thickness of the PCM wall board and the location of the PCM layer were analyzed. The results revealed that at fixed phase change enthalpy, the phase change temperature was the most effective parameter. Figure 51 illustrates the effect of different PCM wall configurations with varying PCM thicknesses on the energy demand in a semi-arid climate, Ankara, and in a mild Mediterranean climate, Marseille, during July.

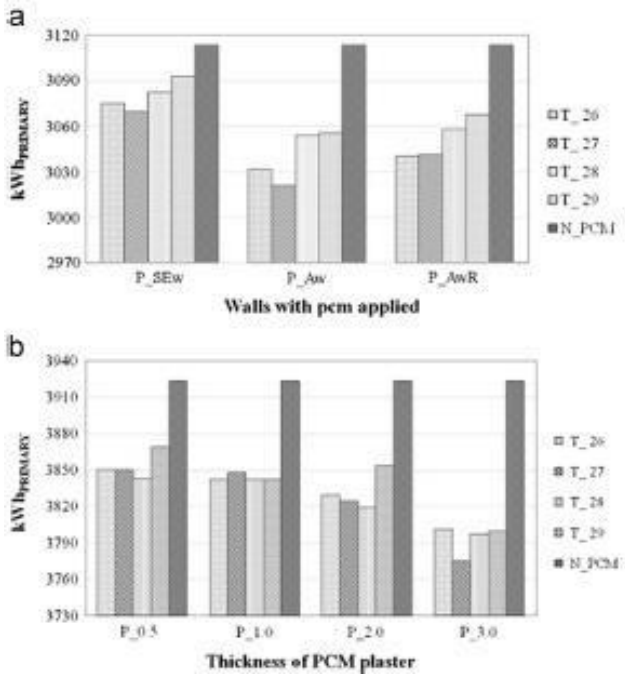


**Figure 51.** Temperature variations inside the PCM cubicle and the reference cubicle and directly measured temperature on the dense sheets.

From figure 51 (a), energy saving rates ranging from 1.4% (0.7%) for the internal face of South and East facades (P_Sew) to 3.0% (1.9%) for Internal face of all vertical facades (P_Aw) can be observed when the melting temperature is 27 °C. The comfort hours increased from 32.9% to 51.0% and from 11.2% to 21.9% for the occupied hours in Marseille and Athens, respectively. In all the investigated PCM wall configurations, the efficiency of the PCM was more effective in a semi-arid climate compared to hot or subtropical Mediterranean climates. From an energy saving point of view, it was concluded that cooling energy saving was strongly dependent on the PCM melting temperature and the cooling season and that using a thicker PCM layer improved the efficiency under the investigated conditions.

Sayyar et al. [40] used experimental and numerical approaches to evaluate the thermal performance of a nano-PCM integrated with gypsum wallboards. The nano-PCM consisted of a fatty acid-based PCM and graphite joined nano sheets. The performance of the nano-PCM walls (test cell) and commercial drywall panels (control cell) in an experimental chamber was compared, as shown in Figure 52.

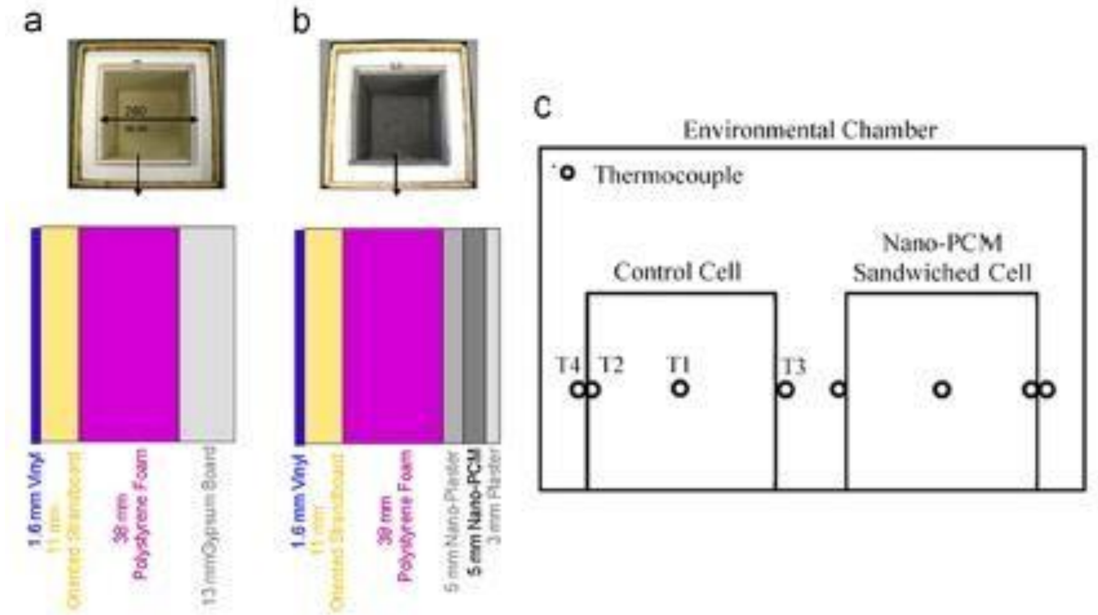


**Figure 52.** (a) Control cell and (b) nano-PCM sandwich cell. (c) environmental chamber. [40]

The results demonstrated the potential of the nano-PCM wall panels to maintain the internal temperature variations from 18.5 °C to 26.5 °C, while the range was 13–32 °C for the control cell. Moreover, the peak load shifting of the test cell with nano-PCMs was 8 hours, which was significantly greater than that of control cell. The new nano-PCMs also improved indoor thermal comfort and reduced energy demand up to 79%.

**Wallboard**

Wallboard is considered suitable for incorporation of PCM because of the following reasons [20]:

- They are economical and commonly used in lightweight construction
- They have larger heat exchange area and smaller heat exchange depth
- PCM is held by them under surface tension forces
- Existing facilities can be used for the production
- Easy of testing

However, as pointed out by various researchers [27], the efficiency of PCM wallboards will depend on various factors such as the PCM selected and its phase transition temperature, the manufacturing technique, the latent heat capacity per unit area of the wall, the orientation of the wall, climate conditions, direct solar gains, ventilation rate and color of the surface.

Ascione et al. [17] investigated the possibility of renovating a building with PCM plaster on the inner side of the exterior building envelope and the effect it would have on energy savings and indoor comfort in the cooling season. The results were simulated while varying the phase change temperature, thickness of the wallboard and the location of the PCM layer. Phase change temperatures ranging from 26◦C to 29◦C were tested. With a melting temperature of 29◦C the highest energy saving potential and increase in comfort hours were seen. However, the achievable benefit for energy savings in climates simulating Seville and Naples were no more than 3%, while Marseille and Athens received a benefit of 4.1 and3.5%, respectively. The highest energy saving effect was reached in Ankara, with energy savings of 7.2%. The comfort hours during the occupied hours increased by 15.5% (Seville), 22.9% Naples, 19.8% Marseille, 15.8% Athens and 20.6% Ankara. This experiment also highlights another important factor for PCMs: during the summer, the period with temperatures lower than the phase change temperature, i.e. the period where the PCM solidifies, would not always be sufficient for the PCM to fully solidify. The same would also occur during the wintertime, where the heat available during the day would not be enough to completely melt the PCM. This indicates that the optimal phase change temperature is seasonal, and complete discharge, or complete absorbance of heat, is difficult to obtain for a single PCM.
The same results were found by Evola et al. [41] performing a simulated case study of an office building refurbished with PCM enhanced wallboards during summer conditions. The wallboards were made of an aluminum honeycomb matrix and filled with 60% micro encapsulated PCMs with paraffin as the core material. This simulation showed that even if the PCMs are frequently activated, on average they only utilized 45% of their total latent heat storage potential, meaning that the entirety of the PCM will not melt or solidify within each cycle. The utilization of total latent heat storage potential is affected by factors such as e.g. convective heat transfer across the wall surface, whether the placement is in areas of a room which receives low amounts of direct solar radiation and climate conditions such as cloudy weather or extreme temperatures that are outside the expected normal temperatures. This study also discussed the importance of evaluating the

PCM over a longer period of time, such as a few months rather than a few days, to be able to better evaluate the activation rate and the utilization rate of the total latent heat storage potential of a PCM under a given climate.

**Gypsum**

Voelker et. al. [42] have developed the gypsum board with integrated microencapsulated PCM, mineral aggregates and have added some admixtures to improve working properties of the board. The incorporated PCM had a melting range between 25 °C and 28 °C. The sensible and latent heat of the material was measured with differential scanning calorimetry (DSC) with a constant heat and cooling rate of 2 K/min.

The developed PCM boards were tested in the special light weight chambers. The two identical test chambers were built next to each other, and in the first one, walls were covered with PCM plaster boards and in the second one with ordinary plaster boards. The thickness of the gypsum board was varied between 1 cm and 3 cm. The test series were carried out under controlled variable conditions. It was discovered that during warm days a reduction of the peak temperature of about 3 K in comparison to the room without PCM could be achieved. On the other hand, temperature in the test chamber was allowed to fluctuate from very low to very high temperatures (approximately 14–35°C). In real building conditions, such high temperature amplitude would not be acceptable and therefore also utilization of the latent heat of PCM in the gypsum boards would be decreased.

Schossig et. al. [43] presented measurements of a full-size room equipped with microencapsulated-PCM plaster boards. Prior to the full-scale measurements, some small scale experiments with specially designed plate apparatus to test wall samples have been conducted. It was discovered that for the samples with PCM temperature instead of rising linearly begins to deflect within PCM melting temperature range. Consecutively, the full-scale measurements have been conducted in the specially built light weight test rooms. One room was equipped with the ordinary reference plaster and the other with the PCM plaster. Both rooms were facing south. In the article, it was not written how much of internal area was covered with gypsum and where the plaster boards were located. The experimental study indicated that PCM gypsum helped to decrease high and low temperature peaks. Over period of 3 weeks, the reference room was warmer than 28°C for about 50 h while the PCM room was only 5 h above 28°C.

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